WOODS HOLE OCEANOGRAPHIC INSTITUTION

Woods Hole, Massachusetts

Reference No. 57 - 9

MARINE METEOROLOGY

On the structure of the Trade Wind Moist Layer

by

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Technical Report #42
Submitted to the Office of Naval Research
Under Contract Nonr 1721(00)(NR-082-021)

January 1957

APPROVED FOR DISTRIBUTION C.O'D. Iselin
Director

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Abstract

Comparison of the lower trade-wind air under conditions of strong versus weak circulation is continued. Moisture and thermal structure and transports from the top of the mixed layer up to the trade-wind inversion are investigated. Much less difference is found at those levels between weak and strong circulation period than was found in the lowest or mixed layer. It is shown that the development of trade cumulus convection is dependent primarily upon conditions below cloud while for immense cumulonimbus build-ups convergence in the large-scale flow appears to be necessary.

A physical model of the moist layer is constructed which describes the interaction of cloud populations with their surroundings. It shows how the cloud groups, though they average level-for-level both virtually and potentially colder than the clear, are thermally direct circulations providing heat and moisture to the trade. The model is built up from numerical calculations based primarily upon the aircraft soundings made in the undisturbed trade near Puerto Rico in April 1946 and March - April, 1953.

I. INTRODUCTION

One of the outstanding features of tropical meteorology is the vertically differentiated structure of the air, with a lower moist layer up to about 2 km, topped by a much drier layer above. The transition zone, a few hundred meters in thickness, is called the trade-wind inversion. It is a region of rapid drying and stabilization in temperature lapse rate but is usually not a discontinuity in wind speed or direction. In the moist layer, convection and convective turbulence are the dominant processes; the air is humid, well-stirred in the vertical and has nearly neutral static stability. Synoptic disturbances are damped downward through the inversion and are generally weak in the surface layer. Above the inversion the air is dry, small-scale convective motions fail to penetrate, and synoptic disturbances are more pronounced.

The trade-wind moist layer forms an early link in the chain of the atmospheric energy supply originating in evaporation from the tropical oceans. The amount of latent energy later released and supplied aloft to the westerlies across the subtropical ridge depends initially upon the accumulation by the lower trades, which in turn depends upon the efficacy of small-scale turbulent and convective processes at the air-sea boundary.

Thus the energy supply for larger-scale circulations, ranging from tropical storms to zonal westerlies, may be partially controlled by fluctuations at the source region. For this reason a study has been undertaken of the varying structure of the low-level trade-wind air. Fortunately, suitable data are now available from one location and season in the Western Atlantic trade in such widely different phases of the index cycle that a maximum contrast should be possible.

Two sets of aircraft temperature and moisture soundings were obtained over the oceans near Puerto Rico (lat. 19°N; 66°W) in the spring season of different years. The first series was obtained during April 1946 by the Wyman-Woodcock expedition (Woods Hole Oceanographic Institution) and later analyzed by Bunker, Haurwitz, Malkus, and Stommel (1949). During this period the trades were strong from the northeast and trade cumulus convection was vigorous. Disturbances were few and relatively weak. Seven years later, in March - April, 1953, the Woods Hole group again visited the region, in collaboration with the Department of Meteorology of the Imperial College, London, and the British National Institute of Oceanography. This time the trades were subnormal and were veered around to south of east for most of the period. Ordinary trade cumulus convection was feeble, although several intense disturbances accompanied by cumulonimbus build-ups passed through.

In a previous report (Malkus, 1956) hereinafter referred to as I, comparison of these two sets of measurements was begun. Synoptic and cross sectional charts were analyzed and it was shown that the 1946 period was typical of high zonal index and strong trade (see Riehl, 1954) while that of 1953, increasingly toward its end, was typical of low index and a trade-wind cell which was running down. In I, the subject of concentration was the temperature and moisture structure in the lowest 500 - 600 m. This report will carry the study on upward throughout the moist layer to the base of the trade inversion, after a brief recapitulation of the problems we desire to illuminate thereby and the results of the preceding studies.

The trade-wind moist layer is itself subdivided in the vertical into two superposed layers of different convective regime, because of the occurrence of water vapor condensation at about 650 m above the tropical oceans. Below the condensation level, in the so-called "subcloud" layer, unsaturated convective turbulence predominates. Eddies 50 - 150 m across are characteristic and recent studies (Malkus, 1957) suggest that larger scales of motion with dimensions 10 - 50 km (size of cloud clusters) are also significant. No evidence of cloud-scale motions below cloud base has been found, except in precipitating downdrafts. Above the condensation level cumulus convection is the major transport process; small-scale turbulence is confined to the neighborhood of clouds, which form in bunches separated by wider weakly subsiding clear areas.

The lower 4/5 of the subcloud layer is well stirred and has been christened the "mixed layer". The lapse rate is close to dry adiabatic and the moisture content of the air is nearly constant, decreasing only 3 - 6% from 15 m above the sea to its top at about

550 m. The thickness of the mixed layer commonly shows variations of 20% in space and as much as 100% in time, with extreme day to day variations of about 300 - 700 m. Recent evidence suggests that its space variations on a 10 - 50 km horizontal scale are associated with the bunchy grouping of trade cumuli. It appears that the cloud groups are situated in places where the mixed layer is thickened, reaching close to the condensation level of the air within it.

Of the vast energy accumulated by the trade, about 75% is latent in water vapor form, and persuasive evidence is appearing that even the 25% increment that is sensible heat is merely an indirect by-product, or the excess of condensation warming over radiative and other losses. It is thus increasingly clear that the main function of the mixed layer in controlling the energy supply to motions ranging in scale from cumuli to global circulations consists in regulating evaporation and carrying upward the evaporated moisture.

The comparison between the 1946 (called series H for high index) and 1953 (called series L for low index) subcloud layers was made in this context with the following specific questions in mind:

1) Why were trade cumuli both sparse and poorly developed in L compared to H?
2) Did the structure of the subcloud air differ markedly between L and H? If so, what were the differences and how might they affect and be affected by larger scale circulations?

The results were presented in I, from which the summarizing tables are reproduced here (Tables 1 and 2, at the back). The mixed layer in the weak trade period was shallower and much less homogeneous moisture-wise, averaging a mixing ratio lapse rate 3.5 times that of the strong trade period. On the poorest days for convection, the condensation level exceeded its top by more than 200 m in clear regions. In the sparsely scattered cloudy regions, the mixed layer top coincided with the condensation level, while in the strong trade situation it fell 87 m short, suggesting the important contribution of wind stirring in carrying subcloud eddies above their equilibrium level. Diminished evaporation during series L was indicated by higher relative humidity at low levels and phenomenally calm seas without white caps. Thus the normal removal of water from the oceans and its upward pumping through the tropical moist layer appears to have been throttled at the input stage during this low index period. The consequences to the remainder of the moist layer will be examined here, and the structure of the cloud layer studied for each period separately and compared.

II. The cloud layer during a period of well-developed trade (April, 1946)

The twenty-five Wyman-Woodcock soundings (methods, instrumentation, and accuracy described by Bunker et al., 1949) were obtained between April 10 - 28, 1946. The time cross section for this period is reproduced in Fig. 1A and a typical surface map in Fig. 2A. Sixteen of the soundings were made in clear areas and nine in cloudy, generally one or more of each type on the same observing day.

Conditions varied relatively little during the observation period, as will be seen when the soundings are studied in detail. Therefore mean clear and cloudy area soundings constructed from the entire series are meaningful, useful in defining terms, and in illustrating the structure of the lower air under conditions of well-developed trade. These mean soundings are presented in Fig. 3. The typical cloudy area sounding (3A) shows a well-mixed layer averaging 625 m depth, with a temperature and virtual temperature lapse rate 85% and 87% dry adiabatic, respectively. The mixing ratio decreases about 0.3 gm/kgm from 15 m to the top, which is the same amount as its average fluctuations. This layer has been studied in detail by Bunker et al. and in I, so is only briefly reviewed here. Cumulus base averages 80 m above the top of the mixed layer, which is defined by a sudden increase in mixing ratio lapse rate and a slight stabilization of temperature lapse rate, which is much more pronounced in clear areas than in cloudy.

The cloud layer is defined for both clear and cloudy areas as the region from the condensation level to the base of the trade-wind inversion, regardless of whether the cloud tops are found below or above. In the cloud layer, the lapse rates of temperature, virtual temperature, and mixing ratio are just in excess of moist adiabatic. A significant feature of the cloudy region cloud layer is that the moisture lapse rate in the upper two thirds averages only 28% that of the lower third, which may thus be regarded as an extended ($\sim$ 400 m) transition zone between saturated and unsaturated convective regimes. The trade inversion is defined by an abrupt increase in moisture lapse rate by a factor of about five and a concomitant stabilization in temperature lapse rate.

In clear areas (Fig. 3B) the mixed layer is 75 m shallower than in cloudy areas and has a 15% steeper moisture lapse rate and 6 - 7% steeper temperature and virtual temperature lapse rates. The main distinction between clear and cloudy soundings lies, however, in the presence of a pronounced shallow transition zone between the mixed and cloud layers. This zone was studied by Bunker et al., who called it the "stable layer". Re-examination of the data in the light of present knowledge has suggested some revisions in nomenclature and interpretation. The "transition layer" will be defined as a narrow stratum just below or above the height of cumulus base in which the moisture lapse rate is not less than twice the average in the cloud layer and an order of magnitude greater than that in the mixed layer below, while the temperature lapse rate is concomitantly more stable than the average for either mixed or cloud layer. Due to the rapid drying, the virtual temperature lapse rate is generally rather steep in the transition zone, of the order of its magnitude in the cloud layer. The latter led to preference for the term "transition" rather than "stable" layer. Using these criteria, we found that a transition layer was always (100%) present in clear zones and generally (55%) absent in cloudy ones. In clear zones, it averaged 200 m in depth, had a moisture lapse rate 22.5 times that in the mixed layer, and temperature and virtual temperature lapse rates 47% and 70% dry adiabatic, respectively. In the cloud layer, the temperature and virtual temperature lapse rates differed only about 3% between cloudy and clear zones, but the moisture lapse rate was half as great in clear areas as in cloudy, partly because in the clear the most rapid drying was confined to the narrow stratum defined as a separate transition zone. Interpretation of these distributions in terms of mechanism will be attempted in the closing sections of this paper. This section will present the data and some calculations therefrom for the transition and cloud layers of the series H (1946) soundings.

For each sounding, the temperatures, virtual temperatures, and mixing ratios were plotted against height and the vertical extent of the transition and cloud layers was determined according to the above definitions. The average lapse rates of temperature, T, virtual temperature, T*, and mixing ratio, w, and average relative humidity, $\overline{rh}$, were carefully determined for each layer as a whole. The results for all the soundings are presented in Table 3 (at the back) and summarized in Table 3A.

The criteria stated previously for the transition layer were met in only four out of nine cloudy area soundings. In four of the remaining five a layer of either somewhat more stable temperature lapse rate or somewhat steeper moisture lapse rate intervened between the top of the mixed layer and the main body of the cloud layer. These cases are included in the averages in Tables 3 and 3A. The problem may be summarized for the present by saying that the transition

Table 3A

Summary of Temperature and Moisture Structure of

Transition and Cloudy Layers

Series H

	Transition Layer						Cloud Layer					
	Depth m	$\Delta\theta$ °C	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Depth m	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Height trade inversion m
Av. clear	197	1.6	0.47	0.70	14.4	81		.63	.69	2.4	76	
Av. cloudy	138*	0.4	0.79	0.995	9.0	88		.61	.71	5.2	79	
Overall Av.	177	1.2	0.57	0.80	12.6	84	1328	.62	.70	3.5	77	2080

*Effectively or totally missing in 5 cases out of 9. Average given for 8 cases out of 9. See text.

is much more sharply confined into a limited height in clear spaces and gradually spread out over the lower 400 m or so of the cloud layer in cloudy spaces. The reasons for this will be examined in Section IV.

The faster upward decrease of moisture in cloudy areas than in the clear appeared intriguing and it was necessary to determine whether this resulted primarily from the spreading out of the transition zone through the lower cloud layer in cloudy areas. The cloud layer was therefore divided into thirds for each sounding and the moisture lapse rate, $-\partial w/\partial z$, calculated separately for each height interval. The results are summarized in Table 4.

The marked difference at all levels between clear and cloudy areas is believed to be a significant key to the processes at work in the trade-wind moist layer and will be dwelt on in detail later.

Table 4

Moisture Structure of Cloud Layer Broken Down into Height Intervals

Series H

$-\partial w/\partial z \cdot 10^8 \text{ cm}^{-1}$

	Lower Third	Middle Third	Upper Third
Av. Cloudy	8.8	4.8	0.3
Av. Clear	2.9	0.5	-0.8
Overall Av.	5.6	2.5	-0.2

(saturated adiabatic $-\partial w/\partial z \cdot 10^8 \text{ cm}^{-1} \cong 2.4$)

Further comparisons between clear and cloudy areas may now be used to resolve a previously disturbing paradox which has misled many tropical meteorologists. All evidence points to mean convergence and ascent in cloudy regions. Despite this, many observers have brought back persuasive evidence that, level for level, cloudy areas are colder than nearby clear areas. Some have brought back measurements inside tropical cumuli showing that the clouds they observed were colder and denser than the surrounding air. The conclusion has been sometimes ventured, therefore, that tropical cumulus and cumulus groups must be thermally indirect circulations, running against negative buoyancy and drawing energy from the kinetic energy of the overall wind flow by some mysteriously produced convergence therein. This misconception has probably contributed to the circuitous philosophy of the general circulation which requires that the trades be maintained by energy conversions outside the tropics and that the oceanic source is drawn on in the indirect and backhanded manner whereby the energy is exported from the trades in latent or potential form, and converted in middle latitudes, whose circulations must then maintain the kinetic energy of the trades which in turn maintain the upward latent energy transport. The grounds for this view collapsed when it was shown (Riehl and Malkus, 1957) that the pressure gradients maintaining the trades are created by energy conversions within them, but the paradox concerning the cloud groups apparently heightened, since it was shown that the cumulus populations were responsible for the net non-adiabatic heating which maintained these pressure gradients! Fortunately enough data has now been gathered to resolve the difficulty.

It is first necessary to establish whether or not cloudy areas indeed average, level for level, both cooler and denser than the surrounding clear spaces. The 1946 data provide this opportunity. There were eight observing days in relatively undisturbed, well-developed trade on which soundings were taken nearly simultaneously in contiguous clear and cloudy areas. Average cloud layer temperatures, virtual temperatures, and mixing ratios were calculated for the same height interval of each sounding on a given day and the values for clear and cloudy areas compared, first considering cloudy area soundings made outside actual clouds. On seven out of the eight days the cloudy areas were colder than the clear by an average of 0.34°C. Since cloudy area soundings averaged 1 gm/kgm wetter than clear, virtual temperatures were next compared. The air near clouds was denser than in clear areas on six out of eight cases, and averaged a virtual temperature 0.27°C less than the clear. Considering the in-cloud soundings themselves, clouds averaged 0.4°C colder than clear areas, 2 gm/kgm wetter and had an average virtual temperature within computational error of the clear area mean for the same day, individual cloud soundings ranging from about 1°C virtually colder to 2°C virtually warmer. Clearly, cloud virtual temperatures could be and often were warmer than the immediate surroundings but colder than the clear areas. Since the expedition deliberately tried to select active clouds it seems proven beyond doubt that averaged space-wise, cloudy areas are both colder and denser than nearby clear areas in the undisturbed trade, regardless of the exact proportion of cloud to clear in cloudy areas. This conclusion is supported by later trade cumulus data obtained by the Woods Hole Oceanographic Institution, using both time-lapse photography and individual cloud traverses in which simultaneous temperature, moisture, and vertical motion profiles were made in selected clouds.

Cloud areas average about a 50% cloud cover. Of the area covered by clouds, about 1/10 is occupied by actively rising towers with a 1 - 2°C positive virtual temperature anomaly, another 1/10 by actively descending downdrafts with a virtual temperature deficiency of about 1°C, and the remaining cloud matter is weakly negatively buoyant ($\Delta T^* \cong 0.1°C$), so that, space-averaged, cloudy areas have a virtual temperature deficiency of 0.1 - 0.3°C. Since all evidence points to mean ascent in cloudy regions, the existence of the paradox seems confirmed. However, the same cloud cross sections point the way out of the confusion. On examining simultaneous virtual temperature-draft profiles, we find that <u>on no occasion was an active updraft negatively buoyant.</u> A few situations of rising, negatively buoyant air were observed, but in each case the updraft was decaying with height or time and just temporarily "overshooting" on its own inertia. Cloud matter was found to be composed of a small fraction of actively buoyant, rapidly rising updrafts, an approximately equal small fraction of actively sinking negatively buoyant downdrafts and a great predominance area-wise of weakly subsiding, slightly negatively buoyant air. A small fraction of these data have been published (Malkus, 1954, 1955) and the remainder is on file at the Woods Hole Oceanographic Institution. The following approximately representative figures in Table 5 are enough to resolve the paradox.

<u>It may be concluded that trade-wind cumulus and cumulus groups are thermally direct motion systems.</u> They run on buoyancy obtained from release of the latent heat of condensation derived from water vapor transported upward from the sea by a combination of turbulent convection and larger-scale (cloud group sized)

Table 5

Distribution of Drafts, Virtual Temperature, and Mixing Ratio Anomalies within a Cloudy Area

Category	Fraction of cloudy area	Draft cm/sec	Mixing ratio anomaly (versus clear) gm/kgm	Virtual temperature anomaly (versus clear) °C
Active updraft	1/20	+330	+2.3	+2.0
Active downdraft	1/20	-150	+2.1	-1.0
Inactive cloud matter	4/10	- 5	+1.7	-0.1
Clear spaces between clouds	5/10	- 4	+1.3	-0.3
Space average		+5 cm/sec	+1.5 gm/kgm	-0.14°C

circulations. The erroneous impression to the contrary was derived from a faulty averaging procedure, understandably arising from a lack of direct draft measurements to correlate with these of temperature and humidity.

The corollary paradox of how a net non-adiabatic heating of trade-wind air is produced by flow through cloudy zones themselves level for level both potentially and virtually colder than their surroundings is now resolvable, but its discussion is reserved for the closing section.

In I it was shown that the air near the ocean surface averaged about 0.1°C warmer in cloudy regions than in clear. At the same time the series H observations showed slightly greater stability in the cloudy region subcloud layer, suggesting that the temperature excess was even a bit greater at cloud base. A study of cloud base level properties confirmed this, showing an excess temperature of 0.2°C, excess moisture of 1 gm/kgm and excess virtual temperature of 0.4°C in cloud zones (away from actual clouds) compared to clear. Evidence published elsewhere (Malkus, 1957) accounts for the excess moisture in cloudy zone subcloud layer in terms of gradual circulations on a 10 - 50 km scale, which appear to be associated with warmer regions in the ocean below. Accounting for the excess temperatures at cloud base in cloud zones will not prove so straightforward and will be attempted here. The vertical motions on the scale associated with cloud groups were deduced to be of the order of 4 cm/sec upward in cloudy areas at cloud base level. Thus if the motions were adiabatic we should expect cooler rather than warmer air at cloud base. If cloudy zones are 10 - 20 km across the cooling should amount to roughly 0.1°C. Since instead we observe relative warming of about 0.2°C, considerable non-adiabatic heating is suggested. The phrasing is made in this way because we know from other data (Riehl et al., 1951) that the trade-wind subcloud layer is accumulating rather than losing sensible heat as it flows downstream (at a rate in the Pacific $\sim$ 0.6°C per day). The present data therefore suggest that near cloud base the warming is occurring more rapidly in cloudy than in clear areas, which in fact must be cooling at this level to give a reasonable net heating downstream. A warming of 0.3°C in 4,000 sec (roughly the time for the trade to traverse a cloudy area) is much larger than the daily rate of non-adiabatic heating required to overcome radiation loss, leaving a net potential temperature increase of 0.6°C per day.

We may now inquire how a large warming at cloud base in cloudy areas could be caused. If real it must be the result of a sensible heat flux convergence. This may be accomplished by radiation, or by motions on a turbulent eddy (50 - 150 m) scale or a cloud group ($\sim$10 km) scale or some combination. Due to lack of knowledge we shall unjustifiably ignore radiation (implicitly assuming that the radiative fluxes vary little at this level between cloud and clear) and inquire into the other two processes. The alternatives are an upward decrease of upward heat flux or a downward decrease of downward heat flux. The evidence greatly favors the latter. Recent measurements (from a 1956 expedition to the area, only partly analyzed so far) indicate that above 30 m or so eddy sensible heat fluxes are downward, of about 10 - 15% the size of the upward latent heat fluxes. While the flux due to the 10-km scale motion is probably upward, the sign of its divergence at cloud base is doubtful. Even if negative a stretching of plausible figures could account at most for one-half the observed warming. On the other hand, fragmentary observations suggest that the convergence at that level of downward eddy flux is of the correct sign and magnitude.

The model suggested by these data is as follows: Some of the condensation heat released in the cloudy zone cloud layer is transported down the potential temperature gradient (downward) by eddy fluxes, which decrease rapidly through cloud base level and toward the surface. In the intervening clear spaces the downward fluxes through the subcloud layer are roughly the same, while the downward flux through the cloud layer is much smaller (due to absence of turbulence away from clouds) and so a flux divergence occurs near cloud base, cooling the air at that level. The net downstream warming indicates that the cooling between cloudy areas is smaller than the warming in cloudy areas and that most of the subcloud layer is being warmed indirectly by precipitation heating. These statements should be regarded as hypotheses only, to be tested further both observationally and theoretically, and not intended to be generalized to all portions of the trades. Supplementary evidence is presented in the closing section, where it is shown that convective precipitation in the cloud layer may warm the air sufficiently to overcome radiation losses and provide enough sensible heat excess for some to be transported down through cloud base level by turbulence.

III. The cloud layer during a period of weak trade (March - April, 1953)

The nine L period soundings were obtained between March 18 - April 7, 1953 in nearly the same locality as those of 1946. The prevailing circulation pattern was, however, markedly different, as demonstrated in I. The time section for the period is reproduced in Fig. 1B and a typical surface chart in Fig. 2B. Briefly we may summarize the differences in overall situation by saying that the L period (1953) trade was weaker, more southerly, and more disturbed than in the H (1946) period. Visually (as recorded by human observer and aircraft nose camera) the striking difference in the 1953 cloud layer was the sparseness of trade cumulus groups. Some evidence also exists to suggest that the L period trade cumuli that did occur were weaker and more poorly developed than those of series H. Comparison of cloud photographs (see Figs. 4A and 4B) suggests that the 1953 cumuli were generally less well organized aggregations of fragments and bubbles, while those of 1946 more often organized into sturdy looking vigorous chimneys. Due to the sampling problem and to the absence of actual draft measurements in 1946, however, this comment may only be regarded as a somewhat subjective impression.

In 1953 only one sounding was made on each observing day, and therefore clear and cloudy areas cannot be compared as was done for 1946. The L soundings were made in cloudy areas on those days when trade cumulus were well developed enough for cloud groups to be easily accessible to the aircraft and in clear regions on those days when trade cumuli were sparse or totally absent. Thus the 1953 data was used in I to compare the mixed layer structure on days favorable to trade cumulus and days unfavorable to trade cumulus. The evidence in I (see Tables 1 and 2 reproduced here) strongly suggested that the sparseness of trade cumuli was explainable in terms of processes occurring below cloud. On poor convective days the absence of wind stirring and diminished evaporation restricted the height of the mixed layer well below the condensation level and suppressed the turbulent upflux of moisture through it. This was so pronounced on the two poorest convection days (April 4 and 5, 1953) that no trade cumulus at all were observed over the oceans! In the 100 odd days that the group has observed in the area, such total absence of oceanic clouds was never duplicated.

The transition and cloud layers for the 1953 period have now been studied. The results are presented in Table 6 (back) and summarized in comparison with the 1946 figures in Table 6A.

Table 6A

Comparison of Series L and H
Transition and Cloud Layers

	Transition Layer						Cloud Layer					
	Depth m	$\Delta\theta$ °C	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Depth m	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Height trade inversion m
1946												
clear	197	1.6	.47	.70	14.4	81		.63	.69	2.4	76	
cloudy	138	0.4	.79	.995	9.0	88		.61	.71	5.2	79	
overall	177	1.2		.80	12.6	84	1328	.62	.70	3.5	77	2080
1953												
clear	125	0.6	.51	.88	24.5	80		.63	.69	3.1	77	
cloudy			Missing					.52	.60	4.6	81	
overall							1343	.58	.65	3.6	79	1932

The striking feature of Table 6A is the similarity of the average figures for the two periods, particularly for the cloud layer.

In series L, the transition layer was totally missing in all but one of the cloudy soundings, in that one it was effectively missing. In the clear soundings it was shallower and had a much greater moisture and virtual temperature lapse rate, which in three cases was 96% dry adiabatic or greater, while the temperature lapse rate itself averaged only slightly less stable than in series H. Those properties calculated in the table for the cloud layer are almost identical for the two periods. On the three worst days for trade cumulus convection, namely April 5, 4 and 2 (in that order) the cloud layer was somewhat shallower, drier, and less stable than the average for either year. These differences must be regarded as consequences rather than causes of poor cumulus development, since on two of those days no oceanic clouds whatsoever were observed. If we break down the cloud layer moisture structure by height intervals (presented in Table 7) and compare with series H, we find some differences. These are, as will be seen in section IV, probably also a consequence of poor convection.

Table 7

Moisture Structure of Cloud Layer Broken Down by Height Intervals

Series L

$-\partial w/\partial z \cdot 10^{8}\ \mathrm{cm}^{-1}$

	Lower Third	Middle Third	Upper Third
Av. Cloudy	4.7	5.1	5.9
Av. Clear	3.5	2.3	5.8
Overall Av.	3.6	3.6	5.8

So far all the evidence suggests that the major reason for the sparseness of trade cumuli in the L period is to be found in the subcloud layer. It further suggests that the shallowness and ineffective transports of that layer were due to a combination of weak flow and southerly flow, the former removing wind stirring and surface roughness, apparently important in evaporation and upward moisture transport, the latter reducing the air-sea moisture and temperature difference (the last is a supposition with no direct evidence to check it). One further important untested possibility remains, namely the degree of convergence or divergence in the large-scale flow. Divergence has been indicated as a major brake upon convection; it acts to bring down drier air, to stabilize, and to widen the spaces between updrafts. When produced offshore of a heated island (horizontal scale smaller than synoptic, magnitude of divergence about ten times synoptic scale) it creates wide cloud-free rings (Malkus, 1955a)primarily by lowering the top of the mixed layer below the condensation level. <u>A priori</u>, therefore, we must consider whether synoptic-scale divergence may not have contributed to a shallower mixed layer during the "poor convection" period of the L series. If we may ignore the relative vorticity compared to that of the earth, the planetary divergence may be estimated from the expression

$$\mathrm{div}_2 \mathbf{V} = -\frac{\beta}{f} v$$

where $\mathrm{div}_2 \mathbf{V}$ is the horizontal velocity divergence, β is the rate of change of the Coriolis parameter, f, with latitude and v is the meridional wind velocity, positive from the south. These results have been entered for each day in Table 6. Examination of the synoptic charts for the period assures that these values are almost surely of the correct sign, although on the disturbed days of March 30 and April 1 the actual convergence was probably about double that given, due to a contribution from cyclonic curvature in the flow. Surprisingly enough we find the exact opposite of what might have been expected: namely, a clearly inverse relation between synoptic-scale convergence and the development of trade cumulus! This apparently horrifying result is clarified, however, by further consideration. It must be recalled that we have been studying the oceanic trade-wind cumulus cloud and not land cumulus nor large oceanic cumulonimbus. The oceanic trade cumulus may be defined as a species of cumulus ranging from about 100 m - 2 km across, 300 m - 3 km in vertical thickness, possessing updrafts from 0.5 - 5 m/sec and exhibiting the typical appearance shown in Fig. 4. We saw that the development of these is largely controlled by the subcloud layer, which is generally most favorable when the flow is rather strongly from the north of east. This maximizes evaporation and upward vapor transport by wind stirring, surface roughness, and maximum air-sea temperature and moisture contrast. With those conditions favorable the trade cumuli seem to function quite well in the face of the average divergence which is of the order of 10^{-6} cm^{-1} (descent $\sim$ 0.1 cm/sec). If, however, the divergence is stepped up by an order of magnitude, as just seaward of a heated island, the mixed layer shrinks and trade cumuli are suppressed.

Oceanic cumulonimbus build-ups, however, are definitely associated with synoptic-scale convergence produced by travelling disturbances.

On the most disturbed days of the L period (March 30 and April 1) cumulonimbus were common over the oceans but the ordinary trade cumuli were very poor. April 1 is particularly interesting. A large line of precipitating cumulonimbi 100 miles east-northeast of Puerto Rico were studied in detail (Malkus and Ronne, 1954). These clouds reached an elevation of nearly 50,000 ft, were 9 km across, and the towers had measured ascent rates of 12 m/sec. At the same time, ordinary trade cumuli were sparse and poorly developed; the aircraft had insurmountable difficulties in obtaining cross sections through any one before it dissipated. If indeed oceanic trade cumulus and cumulonimbus are to some extent mutually exclusive (this is clearly not always so since a good mixed layer and large scale convergence may often coincide, as the writer has frequently observed in the summer season) a very important question is raised: Namely what fraction of tropical oceanic precipitation falls from trade cumulus and what proportion only from cumulonimbus under disturbed situations? This question has enormous implications for the maintenance and steadiness of the trades, and <u>can never be answered from land observations, even those from tiny islands</u>. Tropical island precipitation patterns are controlled by interaction of island effect and trade flow. Their diurnal pattern of cloud production is enormously sensitive to convergence in the large-scale flow. Over islands such as Puerto Rico or Jamaica, in the dry season anyway, even the mountain cumuli rarely reach the cumulonimbus or precipitation stage without the help of at least a weak synoptic disturbance. This observation has been summed up quantitatively over a number of years by Riehl (1950) who shows that 50% of the precipitation of Puerto Rico comes from 10% of the days on which rain fell. The present study suggests that it is not necessarily safe to expect similar curves to prevail over the tropical oceans.

We may now turn our attention to the 1953 trade cumulus clouds themselves and attempt to learn something about their dynamics. It has frequently been stated that on a given day the tops of oceanic clouds are randomly varied downward from the tallest which reach or overshoot the level of zero buoyancy for undilute cores. The reason for the spectrum of heights has been sought. Fortunately the 1953 data was supplemented by a complete series of wide angle motion pictures obtained from the nose of the aircraft during each sounding, on which heights were noted at frequent intervals. A study of these films was made to relate the height of cloud tops to the features of the sounding. For the region and time studied, no continuous spectrum was found on any one day. Masses of small cloudlets generally occupied the lower third of the layer, with their tops occurring at the first rapid drying, ranging from 700 - 1200 m. Tops of medium and larger clouds were generally found associated with regions of rapid drying higher up. On a few occasions when the moisture lapse rate was small and constant, tops of the sizeable clouds were rather uniformly found near the inversion base. On other occasions two or three levels were found within the cloud layer where cloud tops occurred. These levels were readily identifiable as regions of marked drying on the sounding and those clouds which stopped at a given dry layer were generally smaller in cross section than those attaining the next higher level. A very small fraction of the biggest clouds, probably about 1/10 the active population, penetrated a few hundred meters into the inversion layer. In general, however, cloud top distribution gave the appearance of a series of steps rather than a Gaussian curve. This means, of course, that actively rising towers are rare, and that the growth phase of each cloud is short compared to the mature and dissipating period, which has already been indicated in Section II.

Another significant point arising from comparison of the sounding records with the films concerns certain very moist strata of air that were often found near the trade inversion base or sometimes well above it, giving the impression of a multiple inversion. These were usually found to be associated with thin stratus streamers spreading out from the tops of cumuli. Langmuir (during a lecture at Woods Hole, September, 1956) has proposed that this spreading of cumulus tops is important in lateral moisture transfer. It will later be re-examined in this light.

The impression that the cumuli observed during the L series contained weaker and less well organized updrafts than those of the H series has not yet been analyzed. It may have arisen entirely from the sampling problem, in that the sparseness of clouds often forced the observers to settle gratefully for any they could find, or that the few active ones were so far away that they began to die before the aircraft penetrated them. If true, it could be due merely to a poorer supply of fuel (latent heat) from below, or it could be due to an unfavorable wind and/or wind shear field, which has been omitted from Table 6A. The wind field has not been considered previously because proper wind data was not available for the H period, the San Juan RAWINS being neither representative nor detailed enough.

In 1953, the British group obtained frequent double theodolite pilot balloon runs from the small island of Anegada (18°50'N; 64°20'W), so that a detailed wind sounding was generally available within a 20 mile distance and one hour time interval from the aircraft sounding. The wind observations have been analyzed and shearing stresses calculated and reported on in detail by Charnock, Francis, and Sheppard (1956). Although even such a small island produces a marked sea breeze (Malkus, 1957), when we reach the height of cloud base its effect on the shearing field should have diminished. Furthermore, we shall be comparing wind fields within the 1953 sounding series, which were all taken near the middle of the day, so that the sea breeze effect should be approximately constant. Table 8 summarizes the wind structure for the L period cloud layer, the values given in each case being taken from the run nearest in time to the aircraft sounding.

The most striking difference between the good convection and poor convection days (average cloudy versus average clear in

Table 8

Wind Structure of L Period Cloud Layer					
Date	Mean Wind Speed V m/sec	Mean Shear dv/dz m/sec/km	Height Maximum Wind m	Shear Lowest 100m above Cloud Base m/sec/km	Remarks
Mar.18	4	5	780	+2	Little turning below inversion
Mar.21	6	1	750	+0.2	Weak shear Little turning
Mar.25	10	3	936	0	Little turning
Mar.30	2	~2	0(?)	?	Very disturbed Westerlies above 300 m.
April 1	3	3	225	-3.3	Strong veer through cloud layer
April 2	3.5	3	936	-2.6	Wind max 312m at 1600 LST
April 4	6	1.7	624	-4	Wind increase through inversion
April 5	2.7	6	312	-9	90° veer upper cloud layer
April 7	3.4	3.5	330	-4	45° veer upper cloud layer
Av. clear	3.8	3.4	524	4.7	
Av. cloudy	5.8	3.1	699	1.5	
Overall Av.	4.8	3.2	611	3.1	

Table 8) lies in the height of the maximum wind and the shear in the lowest 100 m of the cloud layer, which are probably closely related. The mean wind shear in the whole cloud layer averaged around 3m $sec^{-1}km^{-1}$ for both subgroups, and the best day for cumulus (March 18) had a very large mean shear. The shear in the lowest 100 m of the cloud layer,

however, averaged greater by a factor of three on the poor days for convection. On these days, the trade wind maximum fell considerably below cumulus base and the shear in the lower cloud layer was strongly negative. On the good days for cumulus (except April 7) the wind maximum was usually near or well above cloud base, so that the lower cloud layer was in the region of minimum shear near the turning point. Re-examination of the aircraft cumulus penetrations suggests that vigorous trade cumuli were generally easy to find on days with weak shear near cloud base, although rather strong shears higher up were not fatally inhibitory. Even April 7 fitted in, because by the time the cloud penetrations were made on that day (a few published by Malkus, 1955) the wind maximum was above cloud base and the wind shear in the lower cloud layer was an order of magnitude less (and of opposite sign) than that in Table 8.

Care should be exerted, however, in drawing causal conclusions from the above relations without more controlled and quantitative testing. It may be that strong shear (vorticity about a horizontal axis) at cloud base level inhibits the organization and aggregation of buoyant cloudlets into larger cloud towers and some theoretical evidence (Holmboe, 1955) exists to back this view. It may equally well be, however, that wind maximum at a higher elevation is only a part of the complex of phenomena concomitant with a strongly developed trade situation, other properties of which, such as a good mixed layer, are dominant in determining trade cumulus development.

IV. Moisture transport and its mechanisms in the cloud layer

A physical model describing the processes at work in the cloud layer will be constructed here, primarily for the strong trade situation in which the transports by trade cumulus convection are operating vigorously. The aim will be to explain the distributions observed in the mean soundings for clear and cloudy areas (Figs. 3B and 3A) in terms of mechanism and thus to illuminate the role of the moist layer in the fuel supply for larger scale circulations.

In the previous work by Bunker et al. (1949), a first ori-culation calculation was made to account for the moisture distribution in the cloud layer in clear areas. The authors considered that in the clear zones two processes were at work transporting moisture, namely small-scale turbulence carrying moisture upward and cloud-group-scale subsidence (compensating for the net upward motion in cloudy areas) carrying it down. They assumed, for want of better information at that time, that the observed nearly steady distribution was achieved in situ by a balanced opposition of these two processes. The subsidence rates and eddy transport coefficients obtained were consistent with observed moisture gradients and of a plausible order of magnitude. It was tacitly assumed, although not stated by them, that any net upward flux of vapor was achieved in cloudy areas, the transports in which were not treated then due to insufficient knowledge about cumulus convection.

Observational material obtained since then permits us now to modify and extend their work to construct at least a crude model of clear and cloudy areas together. A large fraction of this material comes from studies of the northern Pacific trade. A vertical section along a trajectory (Riehl et al., 1951) shows that the lower trade accumulates vast amounts of latent heat in flowing downstream. Numerically, the amount is enough to deepen the moist layer by 1 km in 2500 km horizontal travel, and at the same time increase its average mixing ratio by about 1 gm/kgm. In combination this means that an average air parcel increases its mixing ratio by about 0.6 gm/kgm per day. The budget study made of this Pacific section showed that the accumulation was achieved by a convergence of upward moisture flux in excess of that required for precipitation. Those calculations showed that only about 3/4 the water vapor evaporated from the sea surface was carried upward through cloud base, and only about 1/5 that evaporated escaped upward through the inversion. Thus about 25% of the vapor evaporated was exported downstream in the subcloud layer. In the cloud layer, about one-half the gain (55% that evaporated) was recondensed and precipitated and one-half exported downstream. The authors of the Pacific study further showed that cumulus convection alone was easily adequate for the net upward vapor flux through mid cloud layer and to account for the downstream rise in height of its upper boundary. Their picture can be extended and filled in from our more detailed data on the Atlantic trade, provided we can carry over the rough framework of their flux distribution. This is, on the average, clearly well justified since the evaporation rates in the two regions are closely similar and in both regions only a small fraction of the evaporated moisture escapes upward through the inversion base in undisturbed situations. Although this fraction reaching the upper troposphere in the more northerly trade is undoubtedly of considerable importance in the long run, we shall set it equal to zero for the present first orientation, thus assuming that all the moisture evaporated is accumulated in the moist layer and, to maintain the steady state, exported downstream. This implies an upward diminution in net upward moisture flux, roughly as outlined in Table 9 below.

Table 9

Approximate Vertical Distribution of Net Upward Moisture Flux

Evaporation from sea surface $\cong 6.0 \times 10^{-6}$ gm cm^{-2}sec^{-1}

Flux upward through cloud base level $\cong 4.5 \times 10^{-6}$ gm cm^{-2}sec^{-1}

Flux upward through inversion ~ 0

The proportion of evaporated moisture getting up through cloud base has been carried over by assumption from the Pacific trade study; direct vapor flux measurements have been recently made in the Atlantic in 1956 and may be used eventually to check this assumption.

In attempting to explain the moisture distributions of Fig. 3 in relation to these net fluxes, we must bear in mind the observation that in the cloud layer, small-scale turbulence is found only in nearby association with active or recently dissolved clouds. This leads to the following formulation, with which any physical or mathematical description of the cloud layer must be consistant. Eddy turbulent transport is of small importance in clear areas. In cloudy areas it is of importance mainly as a brake upon convection and in achieving exchange of properties between clouds and surroundings. Vertical transports are effected by cumulus and cumulus group scale motions. This will guide us to a model describing the coupling between cloudy and clear areas and the transfer of water and heat from cloudy to clear zones independent of strong lateral mixing and dependent only upon convective circulations superposed on the trade-wind flow. Thus for present purposes, use of eddy exchange or Austausch coefficients for the cloud layer will be avoided, and attention will be concentrated instead upon fluxes and gradients, using what we have deduced above about the former to evolve a mechanistic explanation of the latter.

We shall first show that the upward moisture flux probably occurs entirely in cloudy areas and that the vertical flux in clear zones is almost surely down. For Series H the average mixing ratio in the cloudy zone cloud layer was 11.6 gm/kgm while that in corresponding clear zones was 10.1 gm/kgm. If clear zones average 1.5 times the area of cloudy, the average descent rate in the clear (from Table 5 to meet continuity) is 33 cm/sec. Thus the net upward moisture flux near the middle of the cloud layer is

$$A_{c1} \overline{\rho_{c1} W_{c1} w_{c1}} - A \overline{\rho W_w} = \text{net upward flux} \quad (1)$$

where the subscript " $c1$ " denotes cloudy area properties and the symbols without subscript refer to clear area properties. The A in each case denotes the fraction of the total area; ρ is the air density; W is the vertical velocity in cm/sec; and w is the mixing ratio in gm/gm. The result of (1) can be crudely approximated by

$$A_{c1}\overline{\rho_{c1}W_{c1}w_{c1}} - A\overline{\rho W w} \sim A_{c1}\rho\overline{W}_{c1}\overline{w}_{c1} - A\rho\overline{W}\,\overline{w} \qquad (1a)$$

$$\sim 0.4\times10^{-3}\times5\times11.6\times10^{-3} - 0.6\times10^{-3}\times3.3\times10.1\times10^{-3}$$

$$= 23.2\times10^{-6} - 20.0\times10^{-6} = 3.2\times10^{-6}\ \mathrm{gm\ cm^{-2}\,sec^{-1}}$$

which compares well with the average between cloud base value of 4.5×10^{-6} gm $cm^{-2}sec^{-1}$ and cloud top value of zero. However, it may be objected that setting $\overline{\rho_{c1}W_{c1}w_{c1}} \sim \rho\overline{W}_{c1}\overline{w}_{c1}$ suffers from the same averaging difficulties as discussed in Section II where we showed the serious error in equating $\overline{WT^*}$ to $\overline{W}\,\overline{T^*}$, except that in the present case the result of (1a) must be at least qualitatively correct since even the driest air (between clouds) in cloudy zones is moister than the clear. Indeed, breaking down the cloudy zone flux into transports by strong updrafts, strong downdrafts and weakly subsiding air using Table 5 gives a net flux similar to but somewhat larger than that of (1a), a small difference between large upward transport in cloudy zones and nearly equally large downward transport in intervening clear spaces.

More physical insight, however, is gained if we subdivide the cloud layer vertically into thirds and discuss the flux distribution in terms of gradients of w and W, referring back to Table 4. Table 9 tells us that there is a net flux convergence in the cloud layer averaging about 3.4×10^{-11} gm cm^{-3}sec^{-1}, or if uniform, the net upward flux would decrease 1.5×10^{-6} gm cm^{-2}sec in each third ($\sim$430 m height interval) of the cloud layer. Presumably this may again be a net difference between a rapid upward decrease of upward flux in cloudy zones and nearly equally rapid downward increase of downward flux in the clear. If, as other evidence suggests, the mean ascent rate in the cloud layer increases upward slightly between cloud base and mid cloud layer and then decreases rapidly toward the inversion, we can readily see the necessity for a rapid upward moisture decay in the lower cloud layer superseded by a more gradual one higher up. For the upward flux to decrease from cloud base to mid cloud layer in the face of constant or increasing upward motion, rapid drying must occur. Similarly, subsiding clear areas must average drier than cloudy for a net upward flux and must dry more slowly with height for a smaller flux divergence. A quantitative break down of fluxes as a function of height is attempted in Table 10 (back).

In Table 10, the values of the distribution of average vertical motion in cloudy areas was estimated using the suggestion in Table 5 that the mean value is about 5 cm/sec and evidence (presented by Malkus, 1957) that it increases from a figure of 3 - 5 cm/sec at cloud base to a maximum somewhere between 1 - 1.3 km elevation and then decreases to about zero by inversion base. The mixing ratio values are the observed means from Series H soundings.

The total net flux convergence arrived at in the last column agrees well with the values of Table 9. Since nothing about mechanism has been said, these calculations can in no way be regarded as an "explanation" of fluxes or gradients, even if these very rough figures prove accurate. They merely show that the assumption that the Atlantic trade is accumulating moisture in a similar way to the Pacific trade is consistent with observed gradients and plausible estimates of vertical motions. The vertical motions deduced therein will be used later in a discussion of mechanism.

The striking feature of the moisture transports in the cloud layer revealed so far is the large up and down flux and flux convergence compared to the net transport. The calculated upward transport in cloud areas exceeds the evaporation rate by an order of magnitude. It appears that the moist layer is carrying out a very complex internal re-arrangement of moisture for a small net gain. Actually, a fairly simple and straightforward interpretation of this flux distribution is possible in terms of the scales of motion operating, which forms part of a mechanistic model relating many features and processes in the trades. It will be described here, with the reservation that it is not so firmly established at present that alternatives may be ignored. Reasonably enough, our physical interpretation of the results of Table 10 (and of many other properties of the moist layer) depends upon our views concerning the structure and life cycles of trade cumulus populations, and strangely perhaps, primarily upon whether or not these populations move along with the trade or whether the air moves through them. The alternative models which can be used in accounting for the fluxes of Table 10 are as follows:

1) Individual cloud groups are stationary or moving downstream very slowly, so that the trade moves on the average through them, first undergoing a net rise and then a nearly equal net subsidence (ignoring the overall mean subsidence of 0.1 cm/sec as much smaller). A mean trajectory would look like the sketch in Fig. 5. If trajectories everywhere coincided with mixing ratio isopleths, Table 10 would be superficially little changed, except that the small net flux convergence in the last column would disappear. Moistening at each level would occur in cloudy zones due to convergence and ascent and divergence and descent would undo this in the clear. Actually, the small net accumulation must show up as a slight crossing of trajectory toward higher mixing ratio isopleths in cloudy zones, the two sets of lines becoming parallel on the descent portion in the clear, so that at point B the air at any level is wetter than at A.

2) No relative motion between individual cloud groups and trade winds, but new cloud groups break out and die at rather rapid intervals randomly as the air flows downstream, so that an average trajectory would still look qualitatively like the

sketch in Fig. 5, with more irregular amplitude and spacing of ascent and descent, but still with a hypothetical typical air parcel spending about 4/10 of its time in cloudy regions and 6/10 of its time in clear.

3) Cloud groups occupying the same air for a long time in its travel downstream so that an average air parcel might make one or several complete circuits from the base of the cloud layer to the top and back to the base in clear as the cloudy zone drifts with the wind. This would require the same air to be occupied by cloud for a major fraction of 24 hours; to produce the observed lapse rates of temperature and moisture saturated ascent, mixing, and condensation are required in cloudy areas, and nearly saturated descent with evaporation and mixing are required in the clear. Extended influx of clear air into cloudy regions is necessary near cloud base and horizontal quasi-laminar efflux from cloudy regions at the top of the cloud layer.

4) Cloud groups occupy the same air for long periods and impart moisture and other properties to the clear by lateral mixing.

Model 4 may be discarded without further discussion due to the absence of turbulence in clear areas. Model 3 may be discarded, although less categorically, because in undisturbed situations it is doubtful whether evaporation and nearly saturated descent can be occurring far from clouds; it thus becomes difficult to avoid very high stability and low moisture in the clear. Nevertheless, one of this model's required mechanisms, namely quasi-laminar efflux of moisture from cloud groups at high levels will be reconsidered later in a different connection.

We are therefore led to conclude that in the cloud layer moisture is communicated between cloudy and clear areas - i.e. their structure differs as little as it does - because any given batch of air alternates frequently between being clear and being occupied by cumuli. Whether this is achieved by the trades' flowing through more slowly moving cloud groups, or whether each cloud group drifts with the wind in its lifetime and when it dies a new group forms in different air remains to be seen. A quantitative development of Model 1 will show that it accounts simply for many features of the moist layer and tentatively suggests its preference over Model 2.

Let us consider that trade cumulus groups are either stationary in space or travelling very slowly downwind, so that the air is moving at roughly 5 m/sec relative to the distribution of clear and cloudy areas. Let us suppose that cloudy areas are 20 km across and clear areas 30 km across. An average trajectory in the mid cloud layer would look something like that sketched in Fig. 5, rising about 200 m in the cloudy zone and descending the same amount more gradually in the clear. Of course, any real bunch of air molecules may go up and down several times in clouds, may rise all the way to the inversion, or may actually undergo continuous descent; the mean trajectory only represents an average which becomes more meaningful the wider the cloud group compared to individual clouds and the longer time spent crossing it compared to their lifetimes.

The first step towards a quantitative model is made as follows: We take the vertical distribution of moisture at the downstream edge of a cloud group as given, established by the convection within the cloudy region and past history of the air. We work out the trajectories at selected levels through the next (downstream) clear area, taking a horizontal velocity of 5 m/sec and the vertical motions given in Table 10. Since in its crossing of the clear area the model assumes that trajectories and isopleths of mixing ratio nearly coincide, we get a section like that shown in Fig. 6A.

Only the cloudy area moisture structure and clear area descent rates have been given and yet we arrive at a very realistic clear area moisture structure, averaging drier than cloudy, possessing a rapid-drying transition region in the lower third and an upper portion with a more gradual moisture lapse rate than in cloudy zones, with actual mixing ratio values typical of clear areas. More important, we gain physical insight into the difference between the vertical moisture structure in cloudy and clear areas. If the mean vertical motions first increase with height in the cloud layer and then increase toward the inversion, the necessity for a stronger decay (transition zone) at the base of the layer and a weaker lapse rate above in clear compared to cloudy follows naturally. The close agreement between clear zone figures in Fig. 6 and 3B suggest that the chosen magnitudes for air-cloud group relative motions are reasonable.

In Fig. 6B, 6A is amended to show a more schematic average trajectory through the preceding (upstream) cloud group, giving a 0.1 gm/kgm increase of moisture on each trajectory during its passage through the cloud group. This is roughly consistent with the net flux convergence in Table 10 allowing for precipitation loss. It may thus be useful to regard the flux convergences calculated in Table 10 as largely the result of convergences and vertical motions on a cloud group scale which on the average cancel out as the air moves up and down passing from cloudy area to adjacent clear. In other words, they appear as a consequence of the upward and downward motions of the air trajectories through fixed levels and would disappear if we followed a trajectory. The important small net flux convergence is more profitably viewed as the slight crossing of the trajectories toward higher moisture which is accomplished by cumulus-scale motions, in a manner we shall attempt to describe presently.

First, however, the numbers in Fig. 6B suggest a probable but not conclusive preference of Model 1 to Model 2. If as in the latter, a given cloud group drifted with the air during its entire life, and if the typical lifetime of a cloud group is as long as

3 - 5 hours, the vertical amplitude of the trajectories would be so great that the differences between typical clear and cloudy area soundings would be much larger than observed. The loopholes in this argument are still numerous enough to preclude discarding Model 2. They are as follows:

1. The observations of stationary oceanic cloud groups with lifetimes of 3 - 5 hours have been made from islands and good estimates of population motions and durations over open sea are not yet available. If the latter average as short as 1 - 2 hours, the trajectory amplitude of Model 2 becomes close to that of Fig. 6B, and therefore consistent with soundings.

2. The vertical motions used in Fig. 6B may conceivably be too large. Reduction by a factor of two would also bring the trajectory amplitude of Model 2 close to that in Fig. 6B.

3. Fig. 6B may itself be an understatement of the differences in structure between the downstream end of a cloudy area compared to the downstream end of a clear area, which should be a maximum. The average clear and cloudy area soundings used in the figure were compiled from aircraft ascents located randomly within clear and cloudy areas. Since the mean difference may be considerably less than the downstream ends' extreme, longer average times spent in each type of area than those shown in Fig. 6B are not precluded.

Thus the decision between models 1 and 2 for the undisturbed trade must await further observations on cumulus populations, preferably by photography from a stationary ship. The real situation may lie part way between the extremes, with variations in time and space. In any case, the mean trajectory must qualitatively resemble that of Fig. 6B. In many tropical disturbances, such as slow-moving easterly waves, we can be confident that the trade moves westward through the convective zones and a model of this type will be useful in describing their effect upon the air structure.

The previous paragraphs focuss attention on the vertical moisture structure in cloudy areas, from which, once established, the distribution in clear areas follows simply. We may use recently acquired knowledge of the structure of trade cumulus clouds and cloud groups to evolve a crude qualitative picture of the maintenance of the vertical moisture structure in cloudy regions. Fig. 3A was compiled from soundings in cloudy areas but away from clouds. The moisture distribution in inactive clouds, however, is found to be little different. Therefore, since clear spaces and inactive cloud matter constitute about 9/10 of a typical cloudy area, we may regard for the present rough purposes that the average moisture distribution in cloudy regions is given by Fig. 3A. Nevertheless, it is the active clouds which produce this distribution.

From a study of nine cloud cross sections we find an average vertical moisture lapse rate in active drafts of $3.8 \times 10^{-8} cm^{-1}$, with a tendency to be somewhat steeper in lower and upper portions of the draft than in the middle. In the small sample studied, downdrafts showed only a slightly greater drying rate with height than updrafts. This moisture lapse rate, 160% saturated adiabatic, is established by mixing between clouds and surroundings, the dynamics of which is not yet well known and is beyond the scope of this discussion.

The outstanding features of the moisture structure of the cloud layer as a whole are: The large upward gradient in the lower third, of $8.8 \times 10^{-8} cm^{-1}$ (nearly four times moist adiabatic, which is $\sim 2.4 \times 10^{-8} cm^{-1}$), diminishing to about half this value in the middle third, and almost vanishing in the upper third. This upward reduction in moisture lapse rate can be explained qualitatively in terms of present incomplete knowledge of cumulus dynamics. A clue to the rapid decrease in the lower third is provided by the photographs in Fig. 4 or in fact any typical photograph of trade cumuli. For every medium and large-sized cloud we see enormous numbers of small cloudlets, only a few hundred meters in diameter and thickness. These are commonly found in the lower cloud layer, often clustered around the bases of the larger clouds. It is believed (Malkus, 1954) that the big clouds form from an aggregation of these smaller cloudlets or "bubbles". Photographic evidence strongly suggests that the beginning stages of a cloud population consist of a large number of these, formed from the wetter eddies below cloud achieving condensation in the thicker portions of the mixed layer. Cross sections through individual middle-sized trade cumuli showed that below about 1000 m (above sea level, about 400 m above cloud base) the cloud was composed of several small buoyant elements, which appeared to have fused together into a single more vigorous draft higher up.

The lower third of the cloud layer, then, we may describe as a region of organization, a few strong drafts aggregating from many small cloudlets whose tops vary from heights of about 800 - 1100 m. A region of rapid upward drying is associated with a level where cloud tops are found, the trade inversion itself being the most striking. A rough calculation illustrates the point in the lower cloud layer: Let us suppose there is 5/6 cloudiness at 850 m in a typical cloud group. The cloudy air has a mixing ratio, say, of about 13 gm/kgm and the air which has recently been clear has a mixing ratio of 11.2 gm/kgm (Fig. 3B). The average is 12.7 gm/kgm. These small cloudlets have a lifetime of 5 - 10 minutes, so that air spending one hour or so in a cloudy area should have experienced about ten of them. Turbulent mixing is relatively strong between them and we find consequently that the moisture fluctuations in a traverse through the lower cloud layer are rather small ($\sim$ 1 gm/kgm). If at 1100 m, the active cloudiness is reduced to 1/4, with clouds averaging 12 gm/kgm mixing ratio and air recently clear 10 gm/kgm, the average vapor content becomes 10.5 gm/kgm. These figures agree well with cloud cross sections and the mean moisture distributions of Fig. 3. It may at first seem contradictory that the lower cloud layer is the region of very rapid upward intensification of active updrafts. The cloud cross sections show that the main updraft in a given cumulus may increase by a factor of 3 or even 5 between cloud base and 1 km. However, if the number of updrafts per unit area decreases by almost this proportion, the small calculated increase in net ascent rate from 5 to 6 cm/sec between cloud base and 1100 m is well accounted for. The middle-sized clouds reaching mid-cloud layer or higher have lifetimes of 15 - 30 minutes, so that an average air parcel may enter only 3 or 4 of them during its time spent in a cloudy area. This, plus greatly reduced turbulence aloft between clouds accounts for the larger moisture fluctuations (2 - 3 gm/kgm) on a horizontal cloud area traverse in mid cloud layer, which in fact become even larger as inversion base is approached. The observation that in mid cloud layer the overall average moisture lapse rate exceeds that in active saturated drafts by only about 20% suggests that a considerable fraction of the trade cumuli which get above 1100 m penetrate all the way to the trade inversion, although on individual days regions of rapid drying are often found apparently associated with a "top limit" for certain sizes of clouds. This point cannot be framed more quantitatively at present without more knowledge of cumulus dynamics.

The nearly constant vertical distribution of moisture away from active clouds in the upper portion of the cloud layer is probably produced by the spreading out of cumulus tops. Shelves or streamers of stratus emerging from the upper parts of cumuli are frequently seen to creep gradually across an entire cloud area and even far into adjoining clear spaces. They may be composed of water droplets or ice crystals depending on the elevation. The importance of this phenomenon was suggested by Langmuir[1]. Physically it is envisaged as a nearly laminar spreading out of the cloudy matter as it encounters a stable layer. A similar phenomenon was observed in laboratory experiments on convection at the Imperial College, London (described by Scorer and Ronne, 1956). Bubbles of mud slurry were released into a resting water tank. These moved downward due to excess density. On several occasions the tank contained a lower salty layer which was denser than the bubble fluid, so that each element very abruptly encountered a sudden stabilization of its environment. A typical bubble penetrated only a small fraction of its diameter into the stable layer, and sank back, spreading its material rapidly out laterally <u>above</u> the interface (i.e. on the less stable side). After a few bubbles, the water above the interface became extremely muddied through a considerable depth, while that below the interface remained transparent. It seems likely that a similar mechanism is often at work in the upper trade-wind cloud layer. In this way, even in the absence of wind or wind shear, cloud matter can be dispersed to considerable distances. A crude calculation employing the continuity relation suggests that if a 2 - 3 m/sec updraft 1 square km in cross section is killed in 200 m vertical ascent and if the air spreads out in a wafer 200 m thick in the vertical (this figure is suggested by the depth of

[1]In lecture and conversations at Woods Hole during September 1956.

moist wafers on soundings and observed thicknesses of the stratus sheets), the horizontal velocity of spread is of the order of 4 m/sec at first, or comparable to the original speed of the updraft. Due to the very low values of turbulent friction near inversion base, it is readily shown that the cloud matter may spread several 10's of kilometers before being brought to rest and losing identity by mixing with the surroundings, although the visible cloud particles may not remain that long. Strong wind shear introduces asymmetry and the spreading in one direction may be greatly emphasized (see Fig. 4B).

The moisture gradients in the upper cloud layer and their variations between cloudy and clear zones are thus qualitatively understandable. In cloudy zones the upward moisture decrease becomes very small as inversion base is approached, but does not vanish because new moisture is continually being supplied by cloud activity from below. In the clear, moisture is not being pumped upward from below and the only source is, in fact, in injections at upper levels from cloudy regions. A slight amount of downward diffusion may actually be occurring in addition to the mean transport downward by subsidence of the air itself. Thus in Figs. 5-6, the upper trajectories should perhaps be crossing moisture isopleths toward higher values even in the clear.

All the foregoing discussion has concerned the strong trade situation, when cumulus convection was active. Comparing the cloud layer moisture gradients of the L period with those of the H period

(Table 7 compared to Table 4) we find that in the period of weak trade and poor convection the cloud layer moisture lapse rate averaged only about 10% steeper than the H period but it was much more nearly uniform in the vertical and actually increased from the middle to the top third of the layer. The physical model evolved suggests that the reason was that a smaller fraction of the cumuli penetrated the upper cloud layer and spread out just below the inversion. This is in good agreement with the 1953 cloud photographs and observers impressions.

Thus the moist layer in the L period was drier (average about 0.5 gm/kgm) than in the H period. The trade was also weaker. The combination gives a much reduced downstream moisture export. In the L period a section 1 cm wide and 2 km deep with a wind of 5.7 m/sec and an average mixing ratio of 12.3 gm/kgm exports 140 gm/sec water vapor. The corresponding H period section of the same dimensions (average depths of the moist layer were nearly the same) having a mixing ratio of 12.8 gm and a wind of 9.1 m/sec would export 233 gm/sec. Although these absolute values are too high, since the surface winds for the two periods were used, the point is made that this portion of the trade exported only about 60% of the moisture in the L period as it did in the H period. This figure agrees extremely well with our estimates in I of the reduction in evaporation during the L period. All evidence put together suggests that the Atlantic trade latent heat supply was producing at a significantly reduced rate during at least a month in the spring of 1953. This period of time is long enough and the Atlantic trade a large enough circulation branch to suspect consequences in other portions of the general circulation. It is suggested that the same period and some weeks subsequent be examined further in the equatorial Atlantic, the upper tropical Atlantic and even in the Westerlies and Pacific trade with this background in mind.

Further insight into the actual process of accumulation of latent heat by the trade can be gained from inquiring how trade cumuli actually bring it about. We saw that the net accumulation showed up as a crossing of mean trajectories toward higher moisture content so that after each passage through cloudy plus subsequent clear zone the air returns to its original level slightly wetter than it left. Because of the up and down motion of the trajectories, air leaving the downstream edge of a cloud group at any level must be about 0.2 gm/kgm wetter than air at the same level at the upstream edge for individual parcels to have gained 0.1 gm/kgm. It is readily shown that the shedding of moist air from the active cumuli is an adequate supply. If we take the active drafts (up and down) to occupy 1/10 the area, and if they are 0.8 gm/kgm wetter than their surroundings, normal rates of exchange of air or "erosion" of cloudy matter supplies 0.13×10^{-3} gm/sec to a slice of air 20 km long, 1 cm deep and 1 cm thick. If the mass flux through the slice corresponds to a 5 m/sec wind, the air emerges 0.2 gm/kgm wetter than the air at the same level at the entrance edge.

Thus by bringing up wetter air from below and at any given level exchanging some of this with the drier air at that level, the cumuli act as small "sources" of water vapor for the trade at each height. We may regard this as the accumulation process in the lower and middle cloud layer.

Near the level of cloud tops where the moist layer is increasing in thickness the physical mechanism differs somewhat. In Fig. 5 - 6, except for the slight moistening of the top streamline we have ignored the downstream increase in depth of the moist layer, which should be recalled occurs again by wetting along the trajectories, in the face of actual mean subsidence. As was shown in the Pacific study, this is a very important feature of the trades and was related there to the process of cumulus convection. If this thickening takes place mainly in cloudy regions, it should average about 20 m in each cloud group. That is to say, a wafer of air just above inversion base which on entrance dries about 0.5 gm/kgm through its thickness (from $\sim$ 8.5 to 8.0 gm/kgm) leaves the cloudy area with uniform moisture content. Using the figures presented here, we find that if 10% of the active clouds in the midcloud layer penetrates a net distance of 20 m into the inversion layer and dissolves there, the required moistening is achieved. Clearly individual towers frequently shoot 300 m or more into the inversion layer and they or their dissolved remnants descend back all or most of the way. It is thus better to say that the required moistening is achieved if 10% of the active cloud matter in mid-cloud layer, with allowance for dilution on the way up, is left above the inversion base in the process of cloud tower dissipation.

Thus the net moistening of the air is easily accounted for by ordinary trade cumulus convection and it is not required to call upon cumulonimbus build-ups or disturbances to explain the water vapor accumulation and export by the trade. The question of whether or not we may ignore these for precipitation, however, is considerably more doubtful. Recent studies of tropical oceanic precipitation (Battan and Braham, 1956) indicate that the expectation of precipitation from tropical cumuli is less than 50% if their tops are below about 3 km, probably because the coalescence process requires a minimum time for droplets to spend in cloud. Leaving precipitation physics outside the scope of this discussion, however, it is possible to inquire whether ordinary trade cumuli are able to release adequate liquid water for the observed mean precipitation, even assuming the mechanism for coalescence and fall out is always available. To produce the mean daily rainfall of 0.13 cm (Riehl et al, 1951) each cloud group 20 km on a side must produce about 5×10^{10} gms of precipitation. If active trade cumuli have liquid water contents of 2 gm/kgm (result from unpublished observations at the Woods Hole Oceanographic Institution) and if 1/20 the area is occupied by updrafts 3.3 m/sec strong we find that 52×10^{10} gms of water are condensed and pumped upward in the time the air takes in passing through the cloud group. A study of cumulus downdraft maintenance, however, (Malkus, 1955) suggests that a very large fraction of the liquid water released is consumed by evaporation in downdrafts. Nevertheless, since only 10% of the total is adequate for precipitation, we conclude that ordinary trade cumuli may release enough water to contribute at least a significant fraction of tropical oceanic precipitation. The crux of the entire matter hangs upon the physics of the precipitation mechanism. If a 3 km cloud depth is indeed required, the average undisturbed dry season moist layer 2 km deep is inadequate, and at least a weak disturbance is needed. This is not necessarily true in the wet season, when the undisturbed moist layer is much deeper. The final section illustrates the importance of this question in regard to the non-adiabatic heating of trade-wind air.

V. The production of downstream warming in the trades

The trades are gaining sensible heat as they flow westward and equatorward. This shows up by a motion of the average trajectories toward higher potential temperature, amounting to about 0.6°C per day in the summer season. Riehl and Malkus (1957) showed that this sensible heat accumulation amounted to 25% the latent and was vital in creating the downstream pressure drop required to maintain the trade against friction. A heat budget calculation showed that the net warming was accomplished primarily by an excess of precipitation heating over radiation loss and that the sensible heat provided directly by the ocean was negligible in comparison.

If the addition of heat to the air is accomplished by release of latent heat, it must occur entirely in zones of precipitating clouds. This deduction was apparently paradoxical when compared with the observation that cloudy zones average both potentially and virtually colder than the surroundings. This difference was particularly pronounced in the convective zones of disturbances (Riehl, 1948). The difficulty, however, is readily resolved if we recognize that, particularly in disturbances, the air moves downstream through the more nearly stationary convective zones, first upward in the cloudy region and then downward in the succeeding clear as sketched schematically in Fig. 5. Level for level, therefore, it is potentially and virtually colder within the cloudy zone, but if precipitation occurs the air returns to its initial level potentially warmer than it left. This reasoning can be framed quantitatively for the passage of normal trade-wind air through a group of precipitating trade cumuli 20 km across followed by a clear zone 30 km across. Fig. 7 shows a vertical plot of typical clear and cloudy temperatures and potential temperatures as a function of height (taken from Figs. 3B and 3A respectively) with the calculated trajectories of Fig. 6B superposed. The air ascends in the cloudy region and descends in the clear with the mean velocities of Table 10. <u>While crossing the cloudy zone the trajectories cross isentropes towards higher potential temperature.</u>

Thus the air cools as it rises, but at a rate more nearly moist than dry adiabatic. If the descent in the clear were isentropic, the air would arrive at its original pressure considerably warmed. The consequent warming as a function of height is plotted in the inset graph at the top of Fig. 7. It averages 0.3°C per passage through a cloudy and succeeding clear zone. If the air crosses ten of these in 24 hours, it would gain 3°C per day, which allows for approximately 2°C per day radiation loss and 1°C per day left over for net heating in the cloud and subcloud layer. We have discussed earlier the probable downward flux by eddying of part of this heat to warm the subcloud layer, and the numbers in Fig. 7 are approximately right so when this gain is redistributed it slightly exceeds radiation loss in the observed fashion.

Furthermore, the average precipitation over the tropical oceans, when distributed through the cloud layer in roughly the manner of Fig. 7 is adequate in magnitude to account for the heating, although it remains to be seen whether Fig. 7 applies to areas of typical undisturbed trade cumuli or whether most of the rainfall and heating should be confined to disturbances which would give rarer but much more intense lifting and heating. The proportion contributed by disturbances may differ widely from the dry to wet season and from the upstream to the downstream portion of the trades. That rainfall occurs from ordinary trade cumuli under undisturbed conditions is finally well documented (Palmer, 1956) and the Woods Hole group have obtained several cross sections through such clouds which were precipitating heavily. The question has resolved itself from "whether" to "how much". It is interesting to note that in the relatively undisturbed H period, oceanic cumulonimbus buildups were reported on one day (April 23) and swelling cumulus with tops over 6000 ft on three days (April 23, 27, 28) in each case associated with a weak trough passing the region (Fig. 1A). No information on oceanic precipitation was available. In the L series, precipitating oceanic cumulonimbus were noted on the two most disturbed days (March 30 and April 1) and a large precipitating swelling cumulus reaching 7000 ft was studied in detail on March 21, on which occasion the trade inversion was found at its normal undisturbed height of 2 km.

VI. Concluding remarks

A study of the moist layer in the wet season in the same area, and in other portions of the trade are now required and, in particular, a survey of precipitation as a function of cloud structure and synoptic situation over wide portions of the trade-wind oceans. Fortunately, data suitable to begin such analyses are, or soon will be, available. It is hoped that the physical picture constructed herein may serve as a rough framework to relate these observations, which in turn should be used to improve the physical picture and to fill in many of the vast gaps still visible.

Table I. Summary of Features of Mixed Layer for 1953 (series L) Soundings.

Date	Time	Location	Local Wind Direction	Anegada Wind		Sea	h	Lapse rate of temp. T	Lapse rate of virt. temp. T*	Lapse rate of mixing ratio w	LCL
	LST		° from N	°	m/sec		m	°C/100 m	°C/100 m	x 10^9 cm^{-1}	m
March 18	1450	Cloudy area.	23	18	4	Calm. No whitecaps.	686	.94	.98	29	500
March 21	1400	Cloudy area.	83	93	5	Small waves. No whitecaps.	450	.93	M	M	500
March 25	1115	Cloudy area.	90	89	10	Large waves. Rough white-caps every-where.	550	.82	.90	28	655
March 30	1112	Clear area near edge of cloudy area. High cirrus pres.	Estimated 110	110	5	Medium waves. Some white-caps.	382	.95	.97	28	450
April 1	1045	Clear area near cloudy. Some cirrus Cunimb buildups 70 mi. north.	130	146	4	Small waves. No whitecaps.	382	.95	.98	7.4	580
April 2	1445	Clear area north of small cloudy area. Some cirrus.	118(smoke)	120	4	Sea calm. No whitecaps.	570	1.04	1.05	11	760
April 4	1150	Clear area. No clouds except over islands.	140(smoke)	140	6	Small waves. No whitecaps.	700	.90	.93	13	850
April 5	1300	Clear area. No cu except over islands. Middle clouds 8/10.	130(smoke)	140	7.5	Medium-small waves. No whitecaps.	446	.67	.76	32	855
April 7	0950	Cloudy area.	88(smoke)	96	5.5	Small waves. No whitecaps.	666	.91	.98	15	760
Average			101	105	5.7		537	.90	.94	20.4	653

Table 2. Comparison between 1946 (H) and 1953 (L) Mixed Layers

	h	LCL - h	Relative humidity (bottom)	Relative humidity (top)	Mixing ratio (bottom)	Mixing ratio (top)	Lapse rate of mixing ratio	Lapse rate of temperature	Wind speed		T_{11m}
	m	m	%	%	gm/kgm	gm/kgm	$\times 10^9$ cm^{-1}	°C/100m	°	m/sec	°C
April 10-28 1946(H)											
clear	549	186	71	89	15.0	14.6	- 6.4	.90	87	8.9	25.7
cloudy	620	87	71	91	15.1	14.8	- 4.9	.85	96	9.5	25.8
average	575	150	71	90	15.05	14.7	- 5.8	.88	90	9.1	25.7
March 18 - April 7 1953(L)											
clear	496	204	76	85	15.3	14.4	-18.3	.90	131	5.3	25.6
cloudy	588	14	81	94	15.6	14.2	-24	.90	74	6.1	24.5
average	537	120	78	89	15.44	14.3	-20.4	.90	106	5.7	25.1

Table 3.

Structure of Transition and Cloud Layers for Series H (1946) Soundings

	Transition Layer						Cloud Layer						
Date and Time (local)	Depth m	$\Delta\theta$ °C	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Depth m	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z \cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Height of Trade Inversion m.	Remarks
April 10 1524 hrs clear	216	1.2	0.37	0.58	12.3	87			Sounding ended too low				
April 12 1423 hrs clear	320	1.9	0.48	0.57	10.5	71	1185	0.65	0.67	0.5	61	1885	
April 12 1505 hrs cloudy	116	0.3	0.86 Effectively missing	0.91	2.0	88	Msg.	0.53	0.62	5.4	88	Msg.	Lapse rates only to 1500 m.
April 12 1534 hrs clear	125	2.0	0.56	0.72	6.0	84	Msg.	0.64	0.73	4.6	81	Msg.	"
April 13 1323 hrs clear	275	1.9	0.51	0.67	12.0	79	1770	0.71	0.75	1.7	69	2440	Trade inv. located on radiosonde (San Juan)
April 13 1414 hrs cloudy	110	1.2	0.73 Effectively missing	1.0	3.6	93			Sounding ended too low				
April 13 1454 hrs clear	110	1.2	0.45	0.64	14.5	84			"	" "	"		
April 13 1533 hrs clear	274	2.4	0.04	0.49	21	69			"	" "	"		

Table 3. Continued

	Transition Layer						Cloud Layer						
Date and Time (local)	Depth m	$\Delta\theta$ °C	$-\partial T/\partial z$	$-T^*/\partial z$	$-\partial w/\partial z$	Mean rel. hum %	Depth	$-\partial T/\partial z$	$-\partial T^*/\partial z$	$-\partial w/\partial z$	Mean rel. hum	Height Trade Inv.	Remarks
April 14 008 hrs clear	72	2.1	0.21	0.76	32	83	Sounding ended too low						
April 14 0615 hrs clear	79	1.4	0.34	0.76	16	76	1870	0.66	0.74	2.1	79	2470	
April 14 0720 hrs cloudy	98	1.1	0.76	0.92	14	81	1850	0.65	0.72	2.7	78	2530	
April 22 1854 hrs clear	226	1.8	0.55	0.71	10.5	85	1191	0.65	0.71	3.8	78	1905	
April 23 0713 hrs clear	177	2.1	0.73	0.85	5.2	93	Msg.	0.57	0.63	2.5	91	Msg.	Trough line Cunimb buildups
April 23 1307 hrs cloudy	116	0.2	0.78 Effectively missing	1.0	4.2	93	Msg.	0.64	0.69	3.9	90	Msg.	Portion 700-2000 m only
April 23 1353 hrs clear	190	1.3	0.47	0.76	13.1	89	1860	0.57	0.62	2.6	82	2680	Disturbed day
April 25 1616 hrs cloudy	275	0.2	0.97	1.15 Effectively missing	7.2	89	670	0.58	0.73	8.6	87	1310	
April 25 1646 hrs clear	95	1.4	0.79	0.84	7.2	86	680	0.65	0.79	6.9	81	1265	
April 26 1319 hrs cloudy	85	0.6	0.29	0.53	13.1	86	1000	0.70	0.82	4.6	73	1815	

Table 3. Continued

	Transition Layer						Cloud Layer						
Date and Time (local)	Depth m	$\Delta\theta$ °C	$-\partial T/\partial z$	$-\partial T^*/\partial z$	$-\partial w/\partial z$	Mean rel.hum. %	Depth	$-\partial T/\partial z$	$-\partial T^*/\partial z$	$-\partial w/\partial z$	Mean rel.hum. %	Height Trade Inv.	Remarks
April 26 1416 hrs. clear	183	0.4	0.74	0.93	14.7	82	1420	0.64	0.70	1.5	67	2215	
April 27 0923 hrs cloudy	128	-0.4	1.32	1.6	16.8	92	912	0.64	0.75	6.7	58	1765	
April 27 1025 hrs clear	314	1.7	0.47	0.74	17.5	70	1525	0.65	0.63	-1.15	75	2318	
April 27 1639 hrs cloudy	177	0.4	0.59	0.85	11	82	Msg	0.54	0.65	5.0	82	Msg	Portion 700-2000 m
April 27 1728 hrs clear	192	1.1	0.26	0.62	22	80	Msg	0.53	0.62	1.3	56	Msg	Portion 900-2100 m
April 28 0635 hrs cloudy	Totally missing						Msg	0.61	0.70	5.0	86	Msg	Portion 900-2100 m
April 28 0725 hrs clear	305	1.4	0.54	0.64	16.1	82	1590	0.66	0.68	2.6	77	2440 (raysonde)	"
Clear Av.	197	1.6	0.47	0.70	14.4	81		.63	.69	2.4	76		
Cloudy Av.	138*	0.4	0.79	0.995	9.0	88		.61	.71	5.2	79		
Total Av.	177	1.2	0.57	0.80	12.6	84	1328	.62	.70	3.5	77	2080	

*Effectively or totally missing in 5 cases out of 9. Average given for 8 cases out of 9.

Table 6

Structure of Transition and Cloud Layers for Series L (1953) Soundings

	Transition Layer							Cloud Layer						
Date	Est. planetary div. $10^6 sec^{-1}$	depth m	$\Delta\theta$ °C	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z$ $\cdot 10^8$ cm^{-1}	$\overline{rh}$ %	depth m	$-\partial T/\partial z$ °C/100m	$-\partial T^*/\partial z$ °C/100m	$-\partial w/\partial z$ $\cdot 10^8$ cm^{-1}	$\overline{rh}$ %	Height Trade Inv. (m)	Remarks
March 18 cloudy	1.6	Missing						1311	.59	.65	5.8	90	1835	Uniform cld tops 1600 m.
March 21 cloudy	-0.1	120	0.9	0.5	0.54	6	93	1430	.51	.63	4.2	73	2000	
		Effectively missing												
March 25 cloudy	.07	Missing						1520	.50	.58	2.8	83	2074	
March 30 clear	-.73	188	0.4	0.8	0.96	9	91	3232	.49	.53	2.3	82	3900	Most disturbed day Polar trough. Rain. Cb buildups.
April 1 clear	-1.4	190	0.4	0.79	0.97	10	82	906	.56	.69	6.1	79	1350	Multiple inv. Cb buildups
April 2 clear	-.86	125	1.3	.16	.56	25.6	78	950	.61	.66	1.8	67	1650	Multiple inv.
April 4 clear	-2	90	0.8	0.44	0.89	38	77	977	.71	.77	3.2	77	1767	Worst trade Cu day
April 5 clear	-2.5	30	+0.3	0.33	1.00	40	72	880	.77	.78	2.0	79	1356	Next worst trade Cu day
April 7 cloudy	-0.2	Missing						880	.50	.55	5.8	75	1453	Uniform cld tops
Av. clear	125	0.6	.51	.88	24.5	80			.63	.69	3.1	77		
Av. cloudy		Missing							.52	.60	4.6	81		
Overall Av.	125	0.6	.51	.88	24.5	80		1343	.58	.65	3.6	79	1932	

Table 10

Calculated Moisture Fluxes as a Function of Height in Clear and Cloudy Areas

	Estimated Vertical Velocity $\overline{W}$ (cm/sec)		Observed Mixing Ratio w(gm/kgm)		Flux $\rho\overline{W}w\cdot10^6$ gm cm^{-2}sec^{-1}		Flux Convergence $\cdot10^6$ gm cm^{-3}sec^{-1}		Flux Convergence$\cdot10^6$ times fraction total area		Net Flux Convergence$\cdot10^6$ in height interval
	cld	clear	cld	clear	cld	clear	cld	clear	cld	clear	
Cloud base	+5	-3.3	14.2	12.4	+71	-40.9					
							7.4	-2.1	7.4x0.4 = 2.96	-2.1x0.6 = -1.26	1.7
1/3 way up in cloud layer	+6	-4	10.6	9.7	+63.6	-38.8					
							35.7	-21.4	35.4x0.4 = 14.3	-21.4x0.6 = -12.8	1.5
2/3 way up in cloud layer	+3	-2	9.3	8.7	+27.9	-17.4					
							27.9	-17.4	27.9x0.4 = 11.2	-17.4x0.6 = 10.4	0.8
Inversion base	0	0	~8.5	~8.5	0	0					
											Total flux through cloud base = flux convergence = 4.0×10^{-6} gm cm^{-2} sec^{-1}

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Titles for Figures

Fig. 1. Time cross sections for the two observing periods April 10 - 28, 1946 (H) Fig. 1A, and March 18 - April 7, 1953 (L), Fig. 1B, covering observation days only. Upper winds are RAWINS. A short barb indicates a speed of 5 mph, a long barb 10 mph. Surface winds are in Beaufort scale. The hatched region is the moist layer, the top of which is represented by a dotted line. The base of the westerlies is indicated by a dashed line. The greater strength of disturbances in the 1953 (L) period is suggested by more middle and upper cloudiness.

Fig. 2. Typical surface charts for the two observing periods. In each case the heavy solid line denotes a polar trough. Fig. 2A is the chart for April 12, 1946, 1230 GCT, chosen as typical of period H and Fig. 2B is the chart for March 29, 1953, 1830 GCT, chosen as typical of period L. Note the weaker subtropical high cell and relative north-south elongation of pressure systems on the latter.

Fig. 3. Average soundings for H period, compiled by taking the average temperature, T, virtual temperature, T*, and mixing ratio, w, at the base of each layer (see text), the average lapse rate within the layer of each property and the average vertical thickness of the layer. Height in meters is the ordinate. Fig. 3A is the average cloudy area sounding (compiled from nine

individual soundings) and Fig. 3B is the average clear area sounding (compiled from sixteen individual soundings). Generally one or more soundings of each type was made on a given observing day.

Fig. 4A. Typical trade cumulus cloud photograph of the H period. Made on April 25, 1946 from 20,000 ft altitude. The wind blows from left to right and decreases upward. Note the many vigorous looking chimney-like clouds.

Fig. 4B. Typical trade cumulus cloud photograph of the L period. Made from 6500 ft on March 21, 1953, looking north, so that the trade blows from right to left. The trade inversion is at 2 km (~6500 ft) and the cauliflowerlike top of the cloud is penetrating the drier air. The shelf to the right is formed by the spreading of cloud matter out, primarily downshear, just below inversion base. The "black stratus" in the background was formed in a similar manner. Although this was one of the best days for trade cumulus during the entire L period, the cloud has a holey, fragmentary appearance typical of that observation series. The top continued growing even after the lower portions were almost entirely dissipated.

Fig. 5. Schematic cross section through the moist layer in the plane of the lower trade based on the assumption that cloud groups are stationary or move downstream more slowly than the wind. The solid line (with arrowheads) is an average trajectory, which

ascends in cloudy areas and descends an equal amount in the clear.

Fig. 6. Schematic cross section in the plane of the trade wind showing the average trajectories at several heights (solid lines with arrowheads) and the distribution of mixing ratio in gm/kgm (numbers with decimal points). Fig. 6A shows a clear area. The moisture distribution at its upstream (left) boundary is typical of a cloudy area, while that at its downstream (right) boundary has been rearranged by the descent and its variations with height to be typical of the observed clear area stratification. Fig. 6B has Fig. 6A as its right-hand portion but adds a cloudy area on the left-hand side. Note the slight increase in moisture along the trajectories in the cloudy area. The times are those which the air would spend crossing an area of the given size if it moved through it at 5 m/sec.

Fig. 7. The main portion of the diagram is a vertical cross section in the plane of the trade similar to 6B, with the same average trajectories drawn as the solid lines with arrowheads. This time the three figure numbers (T) with decimal points (to the left of the vertical solid lines) are temperatures in °C and those to the left (θ) are potential temperatures in °A. The column on the far left (upwind side of cloudy area) was taken from Fig. 3B as typical of a clear area and those on the middle vertical line (downwind side of cloudy area) are taken from 3A as typical of a cloudy area. Those on the far right (downstream edge of the following clear

area) were derived by isentropic descent from the downstream edge of the cloudy region. The graph inset above is the resulting net non-adiabatic warming, or the difference in potential temperature on a given trajectory between the far right and the far left, i.e. after a complete passage through a cloudy area and the clear area downstream of it.

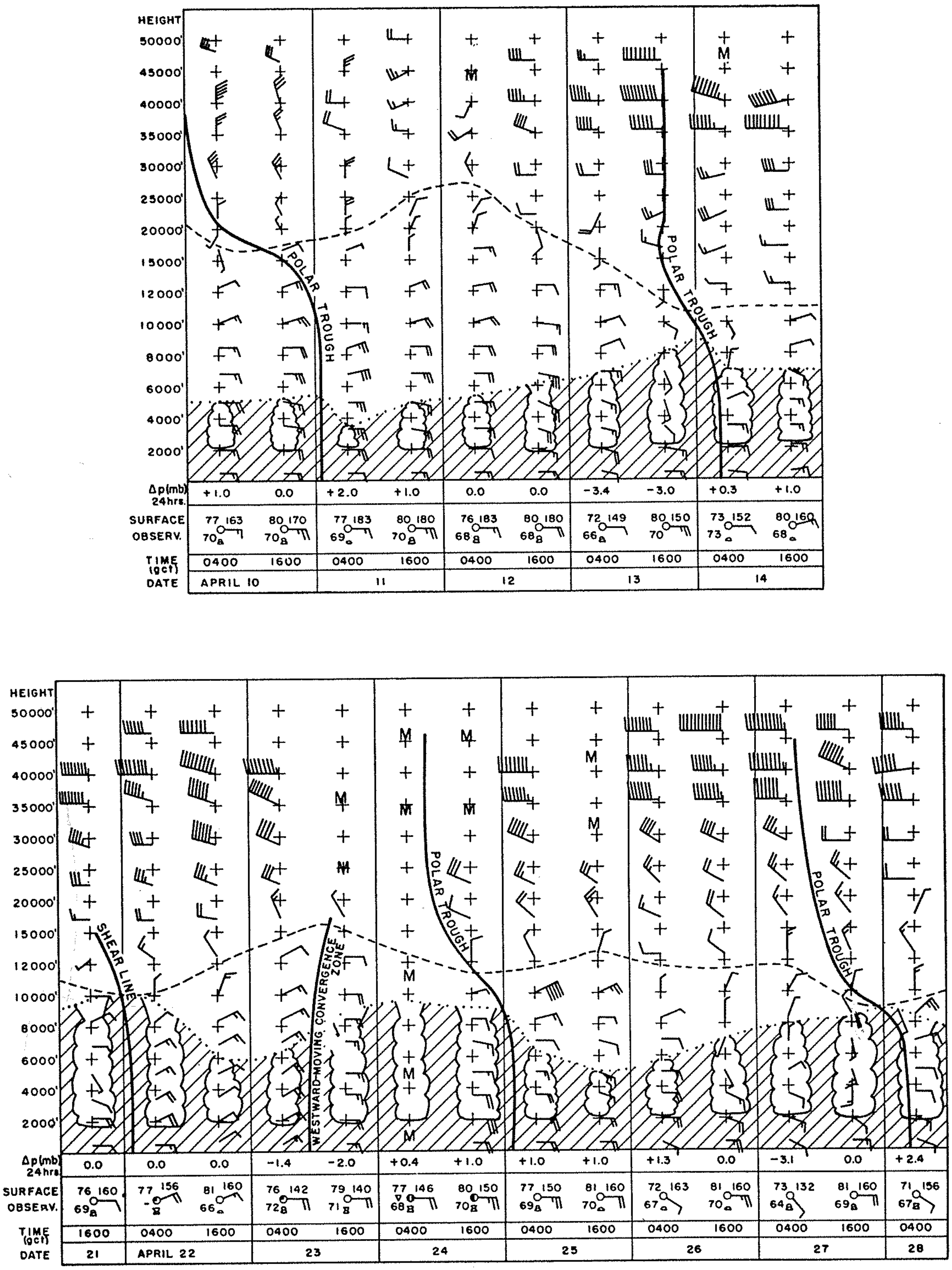

HEIGHT
50000'
45000'
40000'
35000'
30000'
25000'
20000'
15000'
12000'
10000'
8000'
6000'
4000'
2000'
POLAR TROUGH
POLAR TROUGH
Δp(mb) 24hrs.
+1.0 0.0 +2.0 +1.0 0.0 0.0 -3.4 -3.0 +0.3 +1.0
SURFACE OBSERV.
77 163 80 170 77 183 80 180 76 183 80 180 72 149 80 150 73 152 80 160
70 70 69 70 68 68 66 70 73 68
TIME (gct)
0400 1600 0400 1600 0400 1600 0400 1600 0400 1600
DATE
APRIL 10 11 12 13 14
HEIGHT
50000'
45000'
40000'
35000'
30000'
25000'
20000'
15000'
12000'
10000'
8000'
6000'
4000'
2000'
SHEAR LINE
WESTWARD-MOVING CONVERGENCE ZONE
POLAR TROUGH
POLAR TROUGH
M
Δp(mb) 24hrs
0.0 0.0 0.0 -1.4 -2.0 +0.4 +1.0 +1.0 +1.0 +1.3 0.0 -3.1 0.0 +2.4
SURFACE OBSERV.
76 160 77 156 81 160 76 142 79 140 77 146 80 150 77 150 81 160 72 163 81 160 73 132 81 160 71 156
69 66 72 71 68 70 69 70 67 70 64 69 67
TIME (gct)
1600 0400 1600 0400 1600 0400 1600 0400 1600 0400 1600 0400 1600 0400
DATE
21 APRIL 22 23 24 25 26 27 28

FIG. 1A

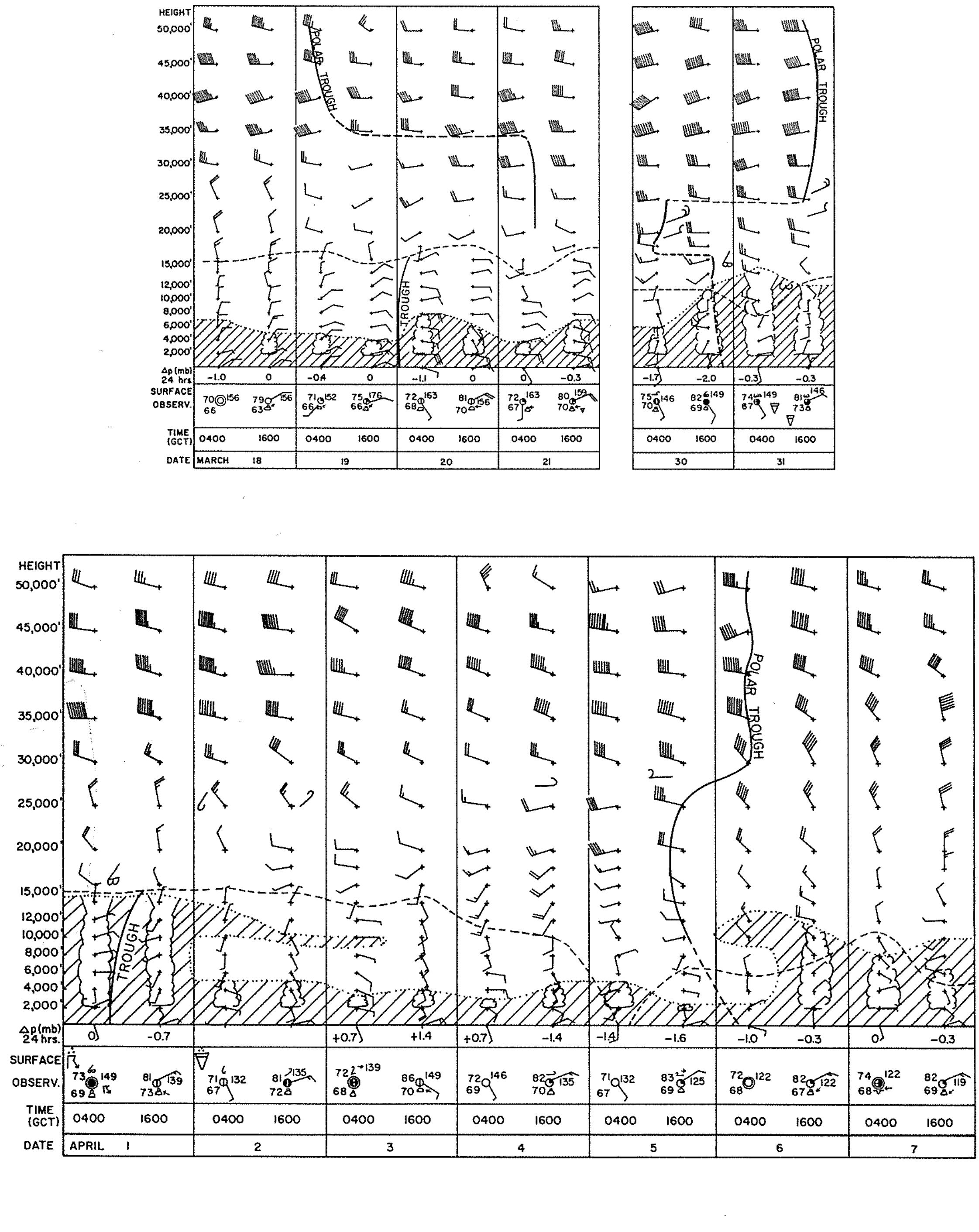

HEIGHT
50,000'
45,000'
40,000'
35,000'
30,000'
25,000'
20,000'
15,000'
12,000'
10,000'
8,000'
6,000'
4,000'
2,000'
Δp (mb) 24 hrs.
SURFACE OBSERV.
TIME (GCT)
DATE
POLAR TROUGH
TROUGH
0400
1600
MARCH 18
19
20
21
30
31
APRIL 1
2
3
4
5
6
7

FIG. 1B

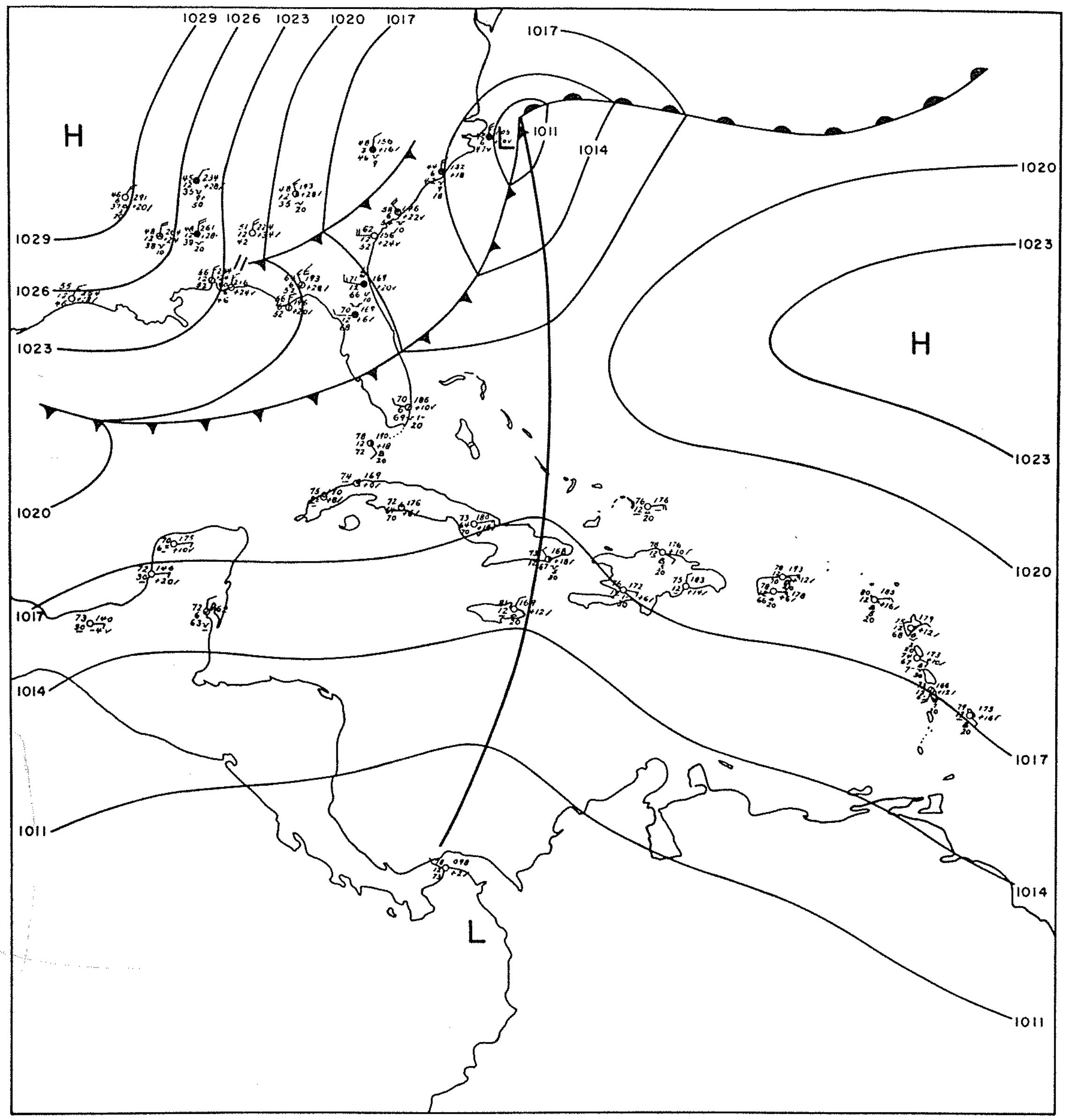

1029 1026 1023 1020 1017
1017
H
1011
1014
1020
1023
H
1023
1020
1029
1026
1023
1020
1017
1014
1011
1017
1014
1011
L

FIG. 2A

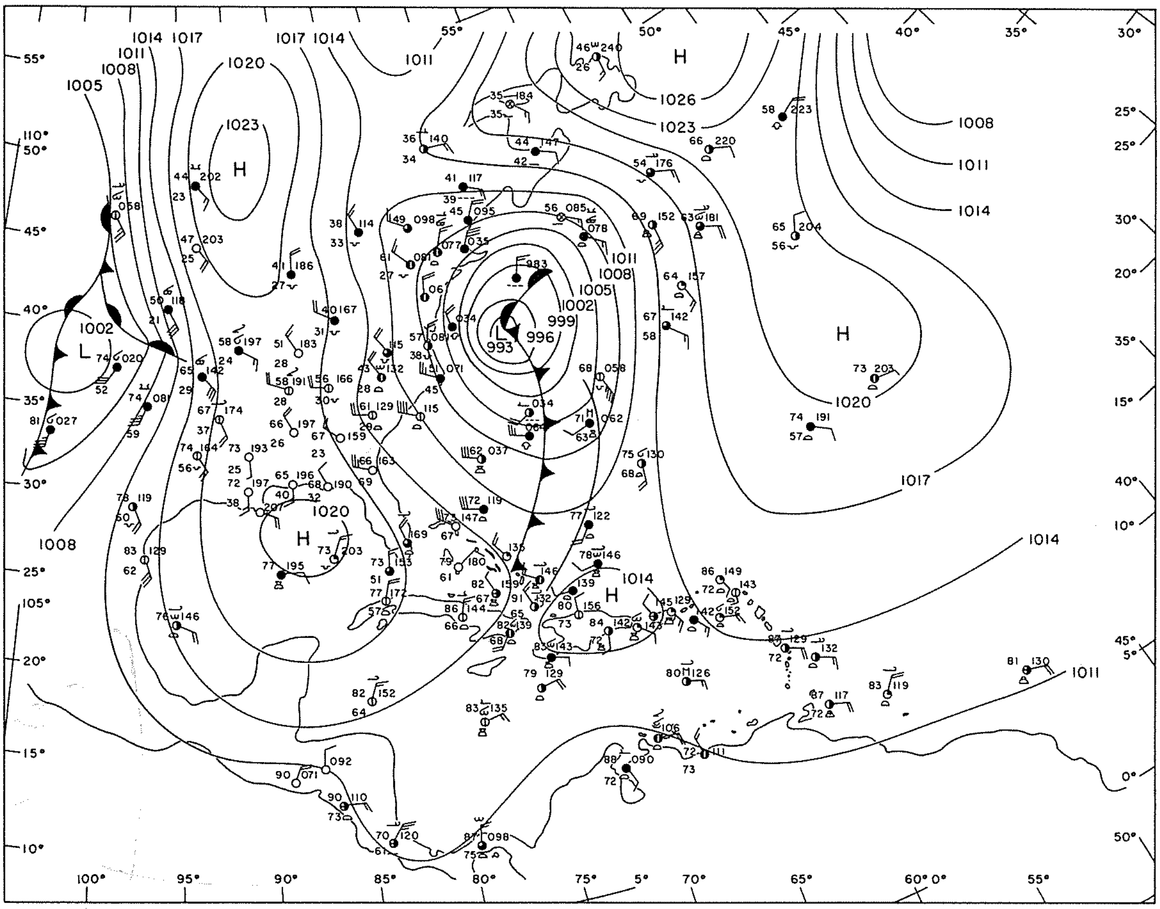
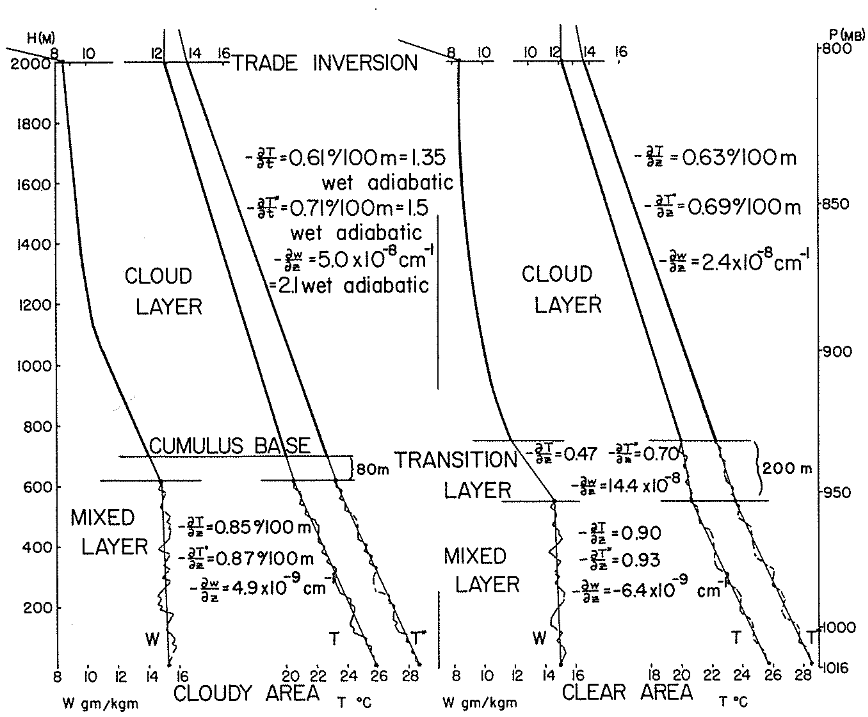


FIG. 2B



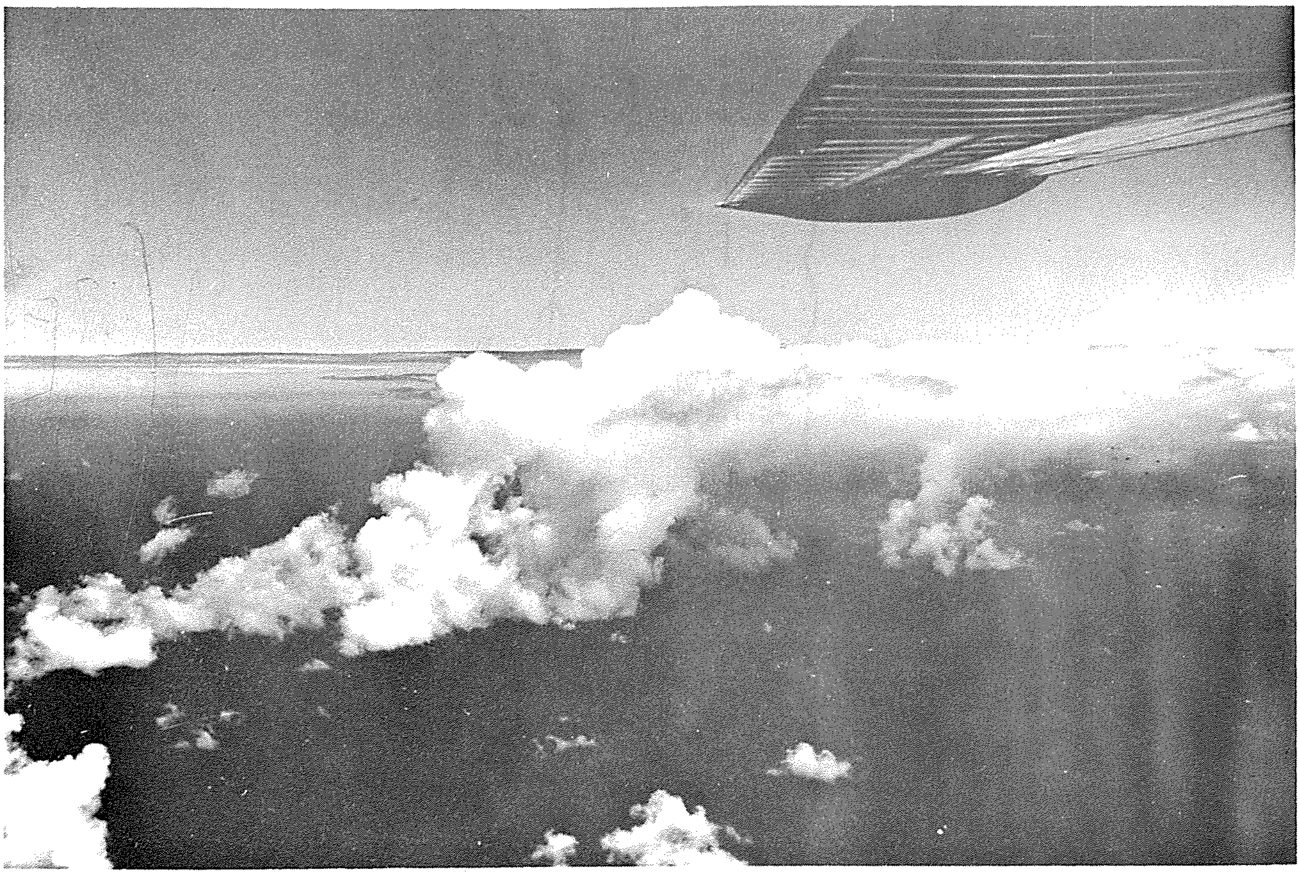
H(M)
P(MB)
TRADE INVERSION
CLOUD LAYER
CLOUD LAYER
CUMULUS BASE
80m
TRANSITION LAYER
200 m
MIXED LAYER
MIXED LAYER
wet adiabatic
wet adiabatic
=2.1 wet adiabatic
W
T
T*
CLOUDY AREA
CLEAR AREA
W gm/kgm
T °C

A

B

FIG. 3

A



B

FIG. 4

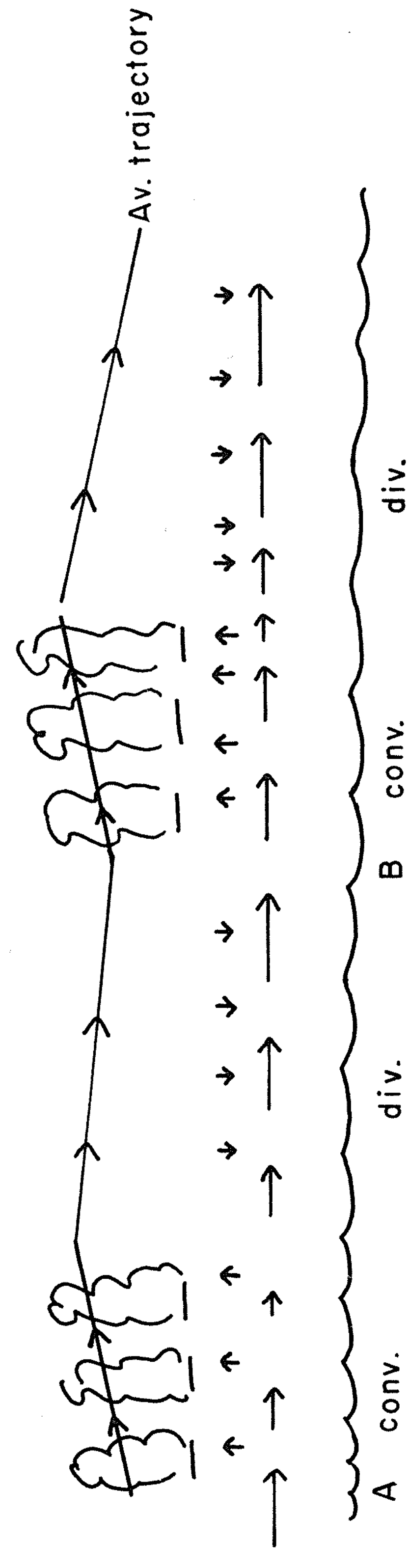


FIG.5

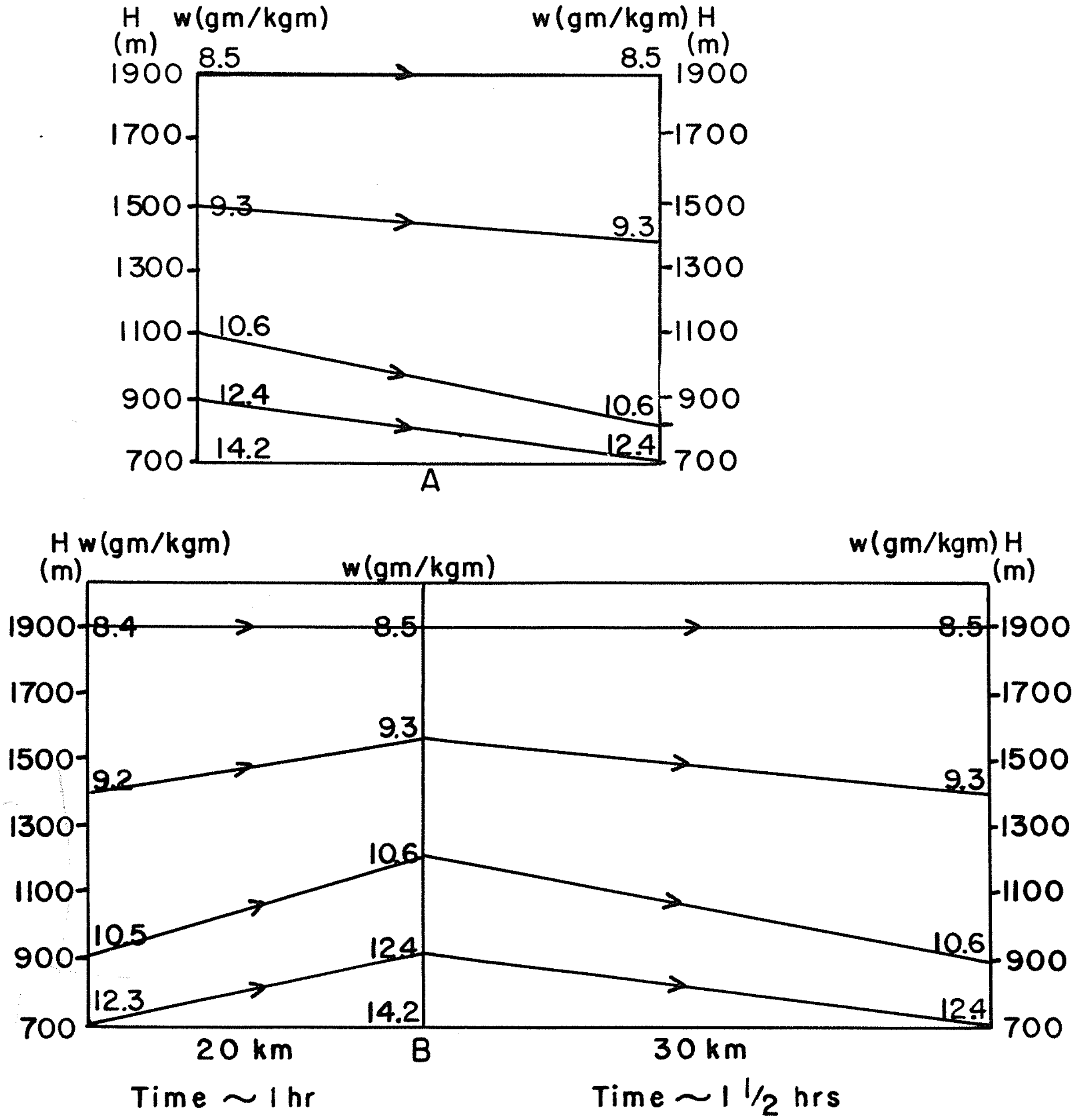
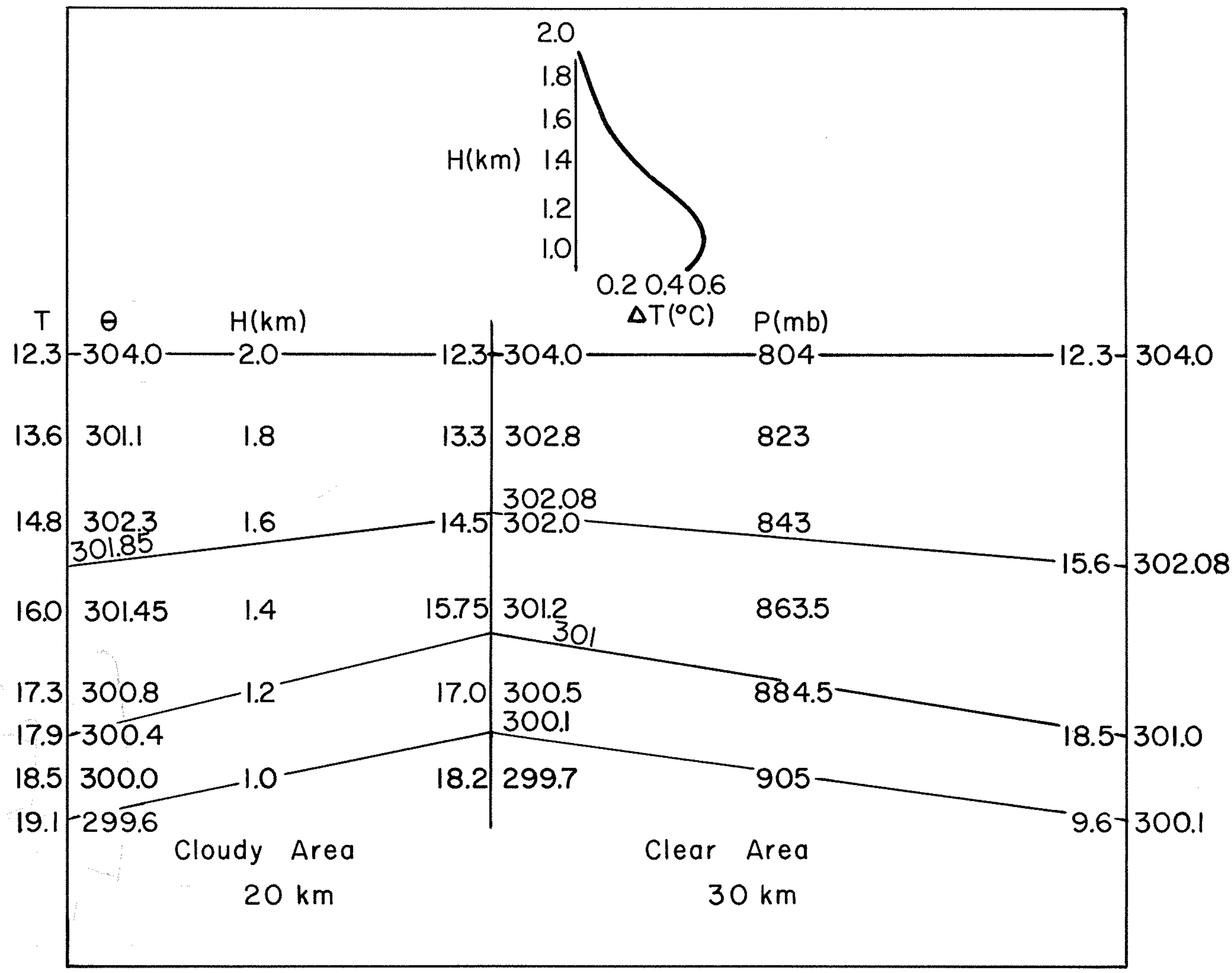

H w(gm/kgm)
(m)
w(gm/kgm) H
(m)
8.5
1900
1700
1500
9.3
1300
1100
10.6
900
12.4
700
14.2
A
H w(gm/kgm)
(m)
w(gm/kgm)
w(gm/kgm) H
(m)
8.4
9.2
10.5
12.3
14.2
B
20 km
30 km
Time ~ 1 hr
Time ~ 1 1/2 hrs

FIG.6



2.0
1.8
1.6
H(km) 1.4
1.2
1.0
0.2 0.4 0.6
ΔT(°C)
T
θ
H(km)
P(mb)
12.3 304.0 2.0 12.3 304.0 804 12.3 304.0
13.6 301.1 1.8 13.3 302.8 823
302.08
14.8 302.3 1.6 14.5 302.0 843
301.85
15.6 302.08
16.0 301.45 1.4 15.75 301.2 863.5
301
17.3 300.8 1.2 17.0 300.5 884.5
17.9 300.4
300.1
18.5 301.0
18.5 300.0 1.0 18.2 299.7 905
19.1 299.6
9.6 300.1
Cloudy Area
20 km
Clear Area
30 km

FIG. 7

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